CHAPTER 3.6

Crusher Selection and Performance Optimization

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CRUSHER SELECTION

The selection of equipment and flow-sheet design considerations for crushing plants cover a wide range of topics. Boyd (2002) gives a comprehensive summary of the factors involved in the design of crushing plants. The principal design parameters are

- Production requirements,
- Capital cost,
- Ore characteristics,
- Safety and environment,
- Project location,
- Life of mine and expansion plans,
- Operational considerations,
- Maintenance requirements, and
- Climatic conditions.

Many of these parameters directly relate to the selection, sizing, and application of crushing equipment. This chapter focuses on these specific factors. A combination of production requirements, ore characteristics, operational considerations, and maintenance requirements are considered. Related to crusher selection, the main issues are

- Stage of size reduction,
- Circuit arrangement,
- Feed characteristics (feed particle size, strength, abrasivity, and materials handling properties),
- Feed presentation,
- Throughput (gross and net), and
- Size reduction and required product size.

Tables 1 and 2 provide a ranking of the crusher types suitable for various stages of size reduction against the ability to treat material with certain characteristics. The number of dots denotes the suitability of different crusher types in relation to feed and performance characteristics. The first table is based on Utley (2002), but with modifications to the crushers considered and updates to account for changes in performance capabilities. Five dots denotes a high level of suitability, whereas one dot denotes that application can be problematic. Within these rankings, the operational and maintenance performance is integral; that is, a poor ability to deal with highly abrasive feed is intrinsically linked to a high maintenance demand.

Priority should be given for the stage of reduction and the suitability to various feed characteristics when selecting crusher types. Providing the crusher type selected is inherently suited to the application, it is a matter of addressing the other factors that will influence how the machine will perform in the role.

Given that crushers can represent either a minor or major component of an overall comminution circuit, it is difficult to characterize a *typical* configuration. Having said this, one of the most often-mentioned characteristics relates to the issue of *open* or *closed* circuit operation. In the open-circuit configuration, the crusher operates as a single-pass machine, and feed is simply transformed into product, which then goes to another processing stage. In the closed-circuit situation, product from the crusher in question is screened, and oversize material is recirculated back to the crusher, while undersize from the screen is sent for further treatment. In general terms, primary and secondary crushers are most often deployed in open circuit, with secondary crusher feed pre-screened to remove material smaller than the closed side setting (CSS), whereas tertiary and quaternary machines are used in closed circuit. The decision to implement open or closed circuits within an overall flow sheet becomes a trade-off between throughput, degree of size reduction required (or possible), cost, and the need for control of the product size for subsequent equipment and processes. A typical three-stage crushing flow sheet is provided in Figure 1, where primary and secondary crushing are open circuit and the tertiary stage is closed circuit.

Generally, the design considerations for feed presentation are related to distribution, rate, and control. There will always be specific issues related to certain types of crusher, but in general, feed presentation should meet the following criteria:

- Maximum feed size should not be greater than 60%–80% of the maximum feed opening (exact number is related to crusher type).
- Feed should be distributed evenly either across the feed opening or where the opening is an annulus (gyratory, cone, and vertical shaft impactor [VSI] crushers) around

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Table 1 Suitability for primary crushing based on feed and performance characteristics

	Gyratory	Jaw-Gyratory	Double-Toggle Jaw	Single-Toggle Jaw	Sizer	Roll Crusher	Horizontal Shaft Impactor	Hammer Mill
Feed size[1]	•••••	•••••	•••••	•••••	•••••	••••	•••••	•••••
Reduction ratio	•••	••••	•••	•••	••	••	•••••[2]	•••••[2]
Throughput	•••••	•••	••[3]	•••[3]	•••••	••••	••••	••••
Feed strength	••••	••••	•••••	••••	••	••	••	••
Abrasive feed[4]	•••	•••	••••	•••	•	••	••	••
Sticky feed	••	••	•	•••	•••••	••	•[5]	•[5]

Adapted from Utley 2002

1. Large feed size in combination with high-strength, high-elastic modulus feed can present problems with nip and ingress to the crushing chambers, as can rocks with low coefficients of friction (i.e., graphite or talc ores). Such issues particularly apply to compression-type machines.
2. Good reduction ratios can be achieved, but only with feed that has a crushing resistance no greater than moderate. For vertical shaft impactor machines, the reduction ratio at the P80 scale is moderate; however, the reduction ratio in the fines area is much greater.
3. Jaw throughput needs to be considered as a total-station value, where a grizzly is incorporated to bypass fines to avoid the crushing chamber. As the percentage of fines varies according to the feed source and type, the overall throughput of the station will be highly sensitive to the quantity of bypass.
4. Abrasivity covers both the flow and gouging wear mechanisms.
5. In some instances, specialized variants are available that will improve the ability to deal with high clay and/or sticky feed.

Table 2 Suitability for secondary, tertiary, and quaternary crushing based on feed and performance characteristics

	Cone	Sizer	Rolls	Vertical Shaft Impactor	Horizontal Shaft Impactor	Hammer Mill
Predominant duty[1]	S/T/Q	S	S/T/Q	T/Q	S/T/Q	T/Q
Feed size[2]	••••	•••••	•••	•••	•••	•••
Reduction ratio	•••••	••	••	••••[3]	•••••[3]	•••••[3]
Throughput	•••••	•••••	••••	••	•••••	•••••
Feed strength	•••••	••	••	•••	••	••
Abrasive feed	••••	•	••	••••[4]	••	••
Sticky feed	••	•••••	••	•	•	•

Adapted from Utley 2002

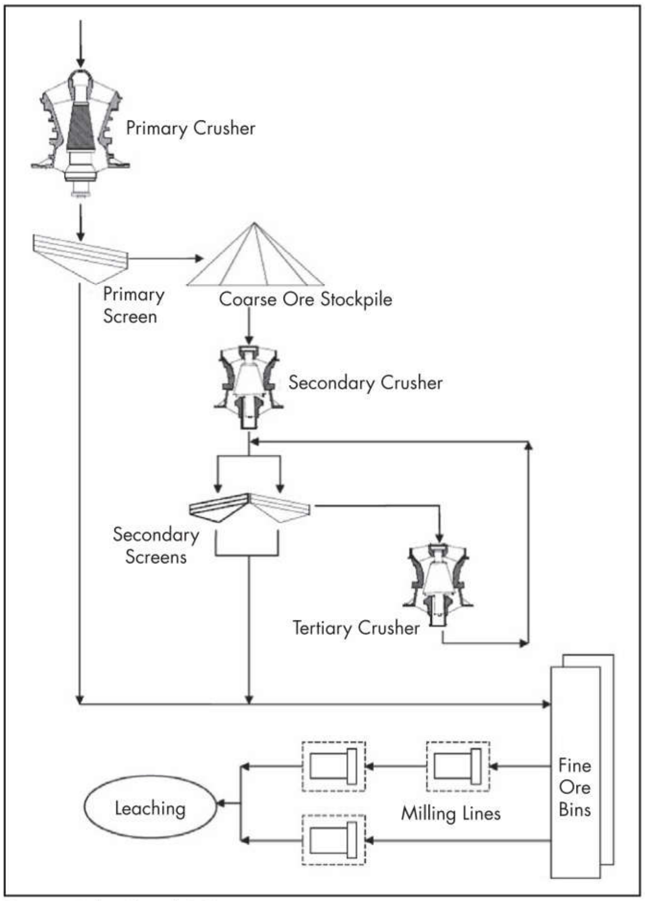
1. S = secondary; T = tertiary; Q = quarternary.
2. Large feed size in combination with high-strength, high-elastic modulus feed can present problems with nip and ingress to the crushing chambers, as can rocks with low coefficients of friction (i.e., graphite or talc ores). Such issues particularly apply to compression-type machines.
3. Good reduction ratios can be achieved, but only with feed that has a crushing resistance no greater than *moderate*. For vertical shaft impactor (VSI) machines, reduction ratio at the P80 scale is moderate; however, the reduction ratio in the fines area is much greater.
4. VSI machines can treat highly abrasive feed, providing the internal configuration is appropriate to the operational conditions.

the opening. The evenness of the distribution needs to apply to both the rate of delivery and also the composition of the feed in terms of size distribution.

- The feed size distribution supplied to crushers differs between machine types. The sensitivity of crushers to the length of size distribution also varies significantly. The inclusion of full-length size distributions (also called *all-in* feed), where fines are present, are known to compact in compression-type crushers, particularly at finer discharge settings (Svensson and Steer 1990). In cone crushers, such compaction is commonly seen in tertiary and quaternary applications but less seldom in secondary duties, except where high reduction ratios are being targeted. There has been a significant trend in recent years to use an all-in feed to secondary cone crushers. This specific issue is addressed in Chapter 3.4, "Gyratory and Cone Crushers." Noncompression machines, or machines where voidage is maintained, including impactors, hammer mills, and sizers, do not cause compaction, and hence the length of the feed size distribution is less of a concern. It can become a concern, however, in cases where the fines are moist or sticky, and this adversely impacts the flow characteristics. In such instances, the presence of fines can cause blockages and build-ups, both within the machine and in peripheral areas.
- Feed rate needs to be controllable, and the ability to control feed depends on the type of feed arrangement, the equipment used, and the flow characteristics of the feed. All crushers should be operated with consistency of feed and rate. In some machines, such consistency is absolutely crucial (e.g., choke feed in cone crushers), whereas in others, it is merely recommended (e.g., sizers, horizontal shaft impactors). The presence of a dedicated feeder is the best option for full control, and Carson and Holmes (2002) provide a review of bins, hopper outlets, and feeders, with additional commentary on certain feeder types provided in Carson and Petro (1998).

Given the importance of feed arrangements, the following paragraphs give an overview of feeder types and applications. The main feeder types encountered related to crushing are vibratory pan, vibrating grizzly, belt, reciprocating plate, or apron. In terms of selection for crusher feed, the main points to be considered when selecting a feeder are

- Robustness (including resistance to impact),
- Particle size,
- Capacity,
- Integral fines removal,
- Ability to handle abrasive material,
- Ability to handle wet and/or sticky material,



Source: Huband et al. 2006

Figure 1 Example of a typical crushing flow sheet with open- and closed-circuit sections

- Physical location (e.g., primary crusher dump pocket, tunnel, stockpile),
- Spillage,
- Dust control,
- Ease of cleaning, and
- Ease of control.

In broad terms, the following statements can be made regarding feeders for crusher installations (Carson and Holmes 2002).

- Vibratory pan feeder
  - Mainly found in duties requiring less than 500 t/h (metric tons per hour)
  - Capable of handling feed up to 300 mm
  - Tolerates a reasonable level of impact
  - Accommodates abrasive feed
  - Accommodates moist material, but may be subject to packing and build-up with wet and/or sticky material
  - Can be enclosed to control dust
  - Well suited to control
- Vibrating grizzly feeder
  - Integral fines removal
  - Highly robust (can be used ahead of primary crushers)
  - Handles run-of-mine (ROM) feed material
  - Tolerates impact
  - Handles abrasive feed
  - Accommodates wet and/or sticky material
- Belt feeder
  - Feed particle size limited to 150 mm
  - Can achieve high rates (3,000 t/h)
  - Not generally applicable where impact is present, particularly if feed is abrasive
  - Not suited to handling wet and/or sticky feed
  - Well suited to control
- Reciprocating plate feeder
  - Highly robust (can be used ahead of primary crushers)
  - Handles ROM feed material
  - Tolerates impact
  - Handles abrasive feed
  - Better suited to free-flowing, nonsticky feed
  - Lags in material flow (feeder action can make control more difficult)
- Apron feeder
  - Highly robust (often used ahead of primary crushers)
  - Handles ROM feed material
  - Good tolerance of impact
  - Handles abrasive feed
  - Better suited to free-flowing, nonsticky feed
  - Requires a *dribble* system to capture and remove fines spillage
  - Action amenable to control

As discussed earlier, there is a need to consistently provide appropriate feed to any crushing unit to provide peak operational and process performance. In terms of throughput—and providing the crusher operates within the acceptable envelope for the integrity of the machine—the main considerations are scoping the base machine for catch-up capacity and ensuring that any throughput sufficiently allows for recirculating load in a closed circuit environment.

Crushers deal with granular material and bulk transport, and therefore availability and utilization are not as high as subsequent grinding equipment. Typically, crushing plants may have mechanical availability of 90% and an equipment utilization of 80%, which gives an overall operation utilization of 72%, compared to milling circuits with values of 92%. In addition, many crushing circuits are decoupled from subsequent processing stages via stockpiles or bins. In this regard, crushers selected for a specific duty need to have a throughput rating that accounts for the lower available operating hours and also gives the ability to run at higher catch-up rates. In designing circuits, individual crushers and ancillary equipment should therefore have a design factor of 1.25 to 1.5 times the nominal rate.

In relation to closed-circuit operation, the balance between the crusher product size distribution, the screen cut size, and the rate of net final product required is critical. Crushers will typically generate 50%–90% passing a nominal discharge setting, and therefore the screen cut size must be set to a value where the tonnage of recycle to the crusher does not accumulate to the point that the circuit is overwhelmed. To ensure that sufficient capacity is available, it is advisable to undertake a circuit simulation of the proposed crusher and screening arrangement using an appropriate software package. Such programs use a convergence algorithm, and if the circuit fails to converge, this indicates that the settings of the crusher and screen cannot be balanced.

All crushers will have a limit for size reduction, usually based on a ratio of feed size (F80) to product size (P80).

Reduction ratio varies by crusher type and the stage in the overall comminution circuit. To calculate the equipment required for the overall reduction needed in a crushing plant, the total reduction ratio should be defined and then compared to that achievable by using combinations of crushers. Table 3 gives typical reduction ratios for various types of crushers.

As an example, if a plant needs to reduce material from a primary crusher feed size of 600 mm down to a final product size of 25 mm, this represents a 24:1 overall reduction. If the application is in medium-hard rock and a gyratory, cone combination is to be used, then by using the values from Table 3, the number of size reduction stages can be calculated. For such feed, average ratios from Table 3 should be used for gyratory and cone crushers, so therefore a primary gyratory in combination with a secondary cone will deliver an overall reduction of (5.5 × 5):1, that is, 27.5:1. Should the feed be harder, and the minimum ratios are therefore used, then it would only be possible to achieve (3 × 3):1; that is, 9:1, and as such, a tertiary stage would be required.

Table 3 Typical reduction ratios achievable by crushers in varying duties*

	Primary	Secondary	Tertiary	Quaternary
Jaw	3–7:1	—	—	—
Gyratory	3–8:1	—	—	—
Cone	—	3–7:1	3–5:1	2–3:1
Horizontal shaft impactor	4–8:1	4–6:1	3–4:1	2–4:1
Vertical shaft impactor	—	3–5:1	2–5:1	2–4:1
Roll crusher	3–5:1	3–5:1	2–4:1	2–3:1
Sizer	3–5:1	3–4:1	2–4:2	2–3:2

*Reduction ratios based on F80:P80 ratio.

Note: Higher reduction ratio values only apply to low-strength, free-crushing feed.

PERFORMANCE OPTIMIZATION

The optimization of crushers and flow sheets containing crushers needs to be targeted to allow the machinery and the circuit to

- Generate the required size distribution, either for final use, or for subsequent processing;
- Provide the required net throughput;
- Apply an optimal level of power to undertake the duties;
- Operate at a level of maintenance costs (direct and indirect) that is a minimum for the required duty;
- Achieve availability and utilization rates that are required to meet the overall production requirements for the operation; and
- Meet operational cost targets.

All crushers are subject to the preceding optimization goals, but depending on the arrangement and use of equipment, certain trade-offs may be required. Overall process optimization for crushers and crushing circuits relies on

- Understanding the circuit mass balance and the performance envelopes of the equipment involved—not only crushers, but classification and materials handling equipment, that is, screens, feeders, conveyor belts, transfer chutes, bins (capacity and residence time), and other external factors (climatic, environmental, etc.);
- Feed strength and abrasivity;
- Feed behavior, such as the inclusion of adhesive clays;
- Feed size distribution (including impact from the performance of screens);
- Feed rate;
- Feed distribution (including segregation);
- Discharge setting;
- Measurement of performance, in terms of crusher liner profile, power consumption, product size distribution, crushing pressure, and recirculating load;
- How the circuit is impacted by classification; and
- Optimization of maintenance activities and schedules for maintenance.

To optimize any circuit involving crushers, the basic requirement is to understand the circuit. During the design phase of mineral processing flow sheets, it is usual practice to assemble the *process design criteria*, which state key parameters that will need to be addressed in the design and the aim of the flow sheet in terms of the performance requirement, that is, throughput, product size distribution, and so forth.

Because of the inherent variability of natural geological materials, the performance of the actual flow sheet will vary from the original intent. If operational practice is overlaid, then the actual performance of the plant can vary considerably from the original plan.

The first step in the optimization of a crushing plant should therefore refer back to the original design inputs and assumptions. This will help with understanding the basis of the original decisions that led to the subsequent design. This original intent should be compared to the actual site parameters, including feed size distribution, specific gravity, bulk density, moisture, strength, throughput, and equipment performance predictions. It is also critical to include the asset management aspects of the actual operation, which would include mechanical availability, utilization of equipment, maintenance practices, and change-out targets. Encompassing both—process and assets—the cost base being achieved must also be compared to those originally estimated.

A key part of the investigation of the design versus actual performance is to establish a full mass balance around the circuit, including total throughput, recirculating loads, size distributions, bulk densities, moisture content, and power consumption. Once established, the settings and performance of the individual equipment units must be assessed, with the assessment also including process control at both the local equipment level and the circuit level. Such an operational survey is at the heart of understanding circuit performance and optimization. For detailed consideration of circuit sampling for granular material and mass balancing, the reader is directed to Napier-Munn (1996). The existence of a well-developed circuit model is the cornerstone of optimization, and the use of this approach allows bottlenecks, inefficiencies, and mismatches to be identified and articulated. Once into the rectification phase of an optimization project, the same model can be used as a virtual test bed for improvements and upgrades.

Key Variables and Measurement Techniques

For a total crushing plant survey, samples for size distribution (and other physical parameters) and throughput at all the key points (such as screens and crushers) in the circuit need to be obtained. The exact method for obtaining a representative survey will be site specific and dependent on the flow-sheet configuration and the ability to safely and effectively access the key points. As a general guideline, a survey of crushing plants should be scheduled so that it corresponds to a period of known feedstock and, if possible, to provide consistency, the feed should come from metallurgically surveyed stockpiles. The feedstock should be sufficient to allow the plant to run consistently for 2–4 hours, during which time all routine data logging should be active. If possible, additional instrumentation should be brought in for the purposes of measuring information not routinely available. Among such additional measurements are conveyor belt speed, crusher countershaft speed, screen motion, and so forth. Once the operation is considered stable, a *crash-stop* needs to be implemented to enable sampling. In certain instances, this may need to be a staged arrangement to prevent blockages or machine stalls. With granular material in crushing circuits, the most effective sampling is to take a known length of material from the relevant conveyor belts. The sample length must be sufficient to provide a representative sample of material based on the top size of the particles present.

Such manual samples are critical to the process, but the entire data set will need to comprise both manual and online data sources.

Throughput is the easiest crusher parameter to measure, and a range of weightometer systems are available in the marketplace. In most instances, the choice comes down to cost, required accuracy, and physical position. Single-idler weightometers are one of the simplest options commonly used in plant process control, but longer multiple-idler systems can achieve higher levels of accuracy and are less susceptible to localized effects. Whichever system is used, it is crucial that it is maintained, calibrated, and also kept clear of excessive spillage. In crushing circuits, it is often the net crusher production that is of interest: In a closed-circuit application with a crusher and screen, it is the screen undersize that is of primary importance. Although this is the operational imperative, sufficient weightometers should be installed in the circuit to allow assessment of the oversize recirculation back to the crushers, as this can be indicative of crusher issues and/or crusher–screen mismatches. As with any equipment, initial calibration and regular verification are essential. Without this, drift in readings can provide a distorted view.

Regarding full product size distribution for operational sites, the options are either to use a sample cutter to physically take a sample from a falling stream of material or by the use of a belt-plow (although this is generally unpopular to the possibility of damage to the conveyor belt). Falling stream samplers come in a range of designs, and providing they take a representation sample, the full size distribution can be manually assessed. Increasingly, optical or automated sizing systems can be used to analyze the sample taken. The other option that is now commonplace is to use either an optical or laser-based online system to assess product size distribution without the need to take a physical sample. Systems such as WipFrag, VisioRock, and Split-Online all rely on taking photographs or video of material on conveyor belts (although they can also be applied to stockpiles or material in truck bodies). Such systems need to be calibrated for the feed material; as in all cases, the systems see the top layer of material and cannot penetrate underneath to measure the rest of the material. The ability to only see the surface of the belt charge means that a correction needs to be applied to predict the finer portion of the size distribution curve. Once calibrated and under consistent feed conditions, such systems can provide a quick and accurate assessment of size distribution.

Power consumption in crushers is simply obtained from meters logging power draw, although in many instances, the output is quoted in amperes. Obviously there are equations to relate power to amperes, but care must be applied because line voltages can differ depending on the power supply and type of motor. Power factors can also be quite variable depending on the load, and any power factor correction that is employed at the site must be understood and incorporated into the assessment.

Hydraulic pressure can be a useful parameter to measure in crushers, such as the primary gyratory and head-adjusted, top-supported cone crushers. In these machines, the hydraulic pressure measured in the system is directly related to the crushing force in the chamber. In such crushers, a pressure transducer in the hydraulic line provides a direct readout into the control system, which can be recorded and logged.

In terms of the internals of the crushing chamber, most forms of crusher have a discharge setting of some description, whereby a physical distance can be set. This setting is critical to the performance of crushers and as such must be recorded. Changes in the setting caused by adjustments for wear or for operational reasons must be logged. Regarding wear, the condition of the liners will contribute directly to the energy applied in the crushing chamber. As such, the wear should always be recorded using a metric suitable for the particular application, with this being throughput or operating hours with reference to a datum. Failure to understand the wear condition of a crusher can lead to incorrect conclusions in relation to crusher and circuit performance.

Online, real-time measurement of crusher discharge settings, or CSS, are routinely gathered, and the method varies depending on the type of crusher. Primary gyratory crushers use the vertical position of the mainshaft to estimate a discharge setting, and a similar approach is used in head-adjusted cone crushers. To obtain the setting and to account for wear, a zero point is required, which is obtained through measuring a metal-to-metal contact (without the crusher running). In bowl-adjusted cone crushers, a zero point is also required, but the CSS is then estimated via the position of the adjustment ring; that is, each tooth will equate to a change at the CSS. Therefore, knowing the number of teeth used for adjustment can provide an indication of the CSS. More sophisticated techniques have been attempted, including laser distance measurement and sensors embedded into the crusher liners, but these have been stymied by operational considerations such as requirements for line of sight and operational durability.

The role of liner profile and liner condition (the worn state) cannot be overstated. Crusher performance and therefore that of the total circuit can drift over time, and in many instances, this drift is directly related to changes in crusher performance from wear on the liners. As crusher performance degrades, control of the crusher product size distribution is lost. This can lead to excess undersize material in the product, or excessive recirculating load, reducing overall throughput. Every site will be different, and there is an inevitable trade-off between liner change-out (including associated costs and downtime) and degradation in crusher process performance. Such a trade-off needs to be carefully considered, and depending on the economics of the operation, there are many instances where liners are removed *early* (in terms of maintenance life) to maintain process performance at acceptable levels.

The role of separation, or classification, can be underestimated in the analysis of crushing circuits. The most common classification devices for crushing circuits are vibrating screens of various types. Screens dictate what material can pass to the next stage of treatment and how much must be retreated to meet the requirements. As such, screens play a crucial part in the overall circuit performance, and additionally, poor screen performance can adversely impact the process and mechanical performance of crushers.

An in-depth analysis of screens is outside the remit of this chapter (for more information, see Chapter 4.1, "Screens." The main factor in crushing circuit optimization is the efficiency of separation. Poor separation can lead to many issues, including misplacement of material, high recirculating loads, and adverse feed size distribution to crushers. The reasons for poor screening efficiency are mainly

- Ineffective screen motion,
- Feed rate,
- Feed size distribution and percentage of near-cut size material,
- Sticky material causing blinding of the screen media,
- Bed thickness,
- Selected cut size,
- Aperture shape, and
- Stiffness of screening media.

One of the most common negative effects seen in terms of crushing circuit performance relates to the situation whereby a screen is set to recirculate oversize back to a crusher. A worst-case scenario is as follows:

- The crusher product sent to the screen is not efficiently separated (because of the factors stated previously).
- Oversize from the screen is sent back to the crusher with a high content of undersize.
- Undersize is not crushed effectively and again returns to the screen as *near-sized* material.
- Near-sized material close to the aperture size further hinders separation.
- Screen efficiency drops further, and more undersize is sent back to the crusher.

This vicious circle contains both inefficient screens and consequently inefficient crushers. In tandem, the impact on the net throughput of the circuit can be damaging. Outside of the throughput issue, cone crushers also tend to suffer if the fines percentage in the feed is high. The main effect seen is an increased incidence of *packing* in the chamber, and this can also lead to mechanical failures.

Feed Properties

Feed properties have a direct and quantifiable impact on crusher performance. The main factors are

- Strength,
- Feed size distribution,
- Abrasivity and abrasive mineral content,
- Moisture content,
- Clay content, and
- Density.

Crushing Strength

Crushing strength can be measured in many ways. There are other chapters in this handbook that review the Bond work index and the JK drop weight and semiautogenous mill comminution tests.

In addition to these tests, a further range of parameters can be quoted in relation to crushing performance. The following list gives the most commonly encountered *strength* values seen in relation to crushing, with all of these tests coming from the rock mechanics discipline:

- Uniaxial compressive strength
- Brazilian tensile strength
- Young's modulus
- Poisson's ratio
- Point-load strength
- Fracture toughness
- Schmidt hammer
- Sonic (P-wave and S-wave [longitudinal and transverse]) velocities

Most of the tests listed above are index tests; in other words, they are values to allow the user to place a rock in comparison to others. Index tests are useful and can provide an idea as to the relative crushability of rock; equally, some care must be taken in this approach. As context, previous work has examined relationships with crushing and also general correlations between geotechnical parameters. On the basis of these previous studies, a generalized statement is summarized in Table 4.

The following are the most important points to consider when examining index values:

- The source of the material and the potential for the sample to contain pre-weakening cracking sustained in the sample preparation
- The mode of failure induced during the test
- The *standard* used for tests and the adherence to the standard conditions
- The variability of the test data
- Consideration of strength anisotropy because of bedding, banding, or lineation within the rock type

For crushing, the most appropriate tests are those that show the purest form of tensile failure. As tests deviate from pure tensile failure, the results start to reflect the test geometry and the conditions rather than an inherent property of the rock. In this regard, fracture toughness and indirect tensile strength (ITS) are the most tensile-based tests and, therefore, those with the strongest relationship to crusher performance.

Fracture toughness comes from the fracture mechanics domain and is designed to determine the critical stress intensity factor, that is, the stress required to cause catastrophic crack extension. There are several tests designed to deliver a pure tensile condition and to allow measurement of the critical stress intensity (K), that is, fracture toughness. For crushing, it is sufficient to test for the mode I fracture toughness, which relates to tensile failure. Other fracture toughness modes can also be tested, but these introduce mechanisms such as shear and are less appropriate for crushing.

The International Society for Rock Mechanics (ISRM) has introduced standards for a variety of fracture toughness techniques, including the chevron bend (Figure 2), short rod, and semicircular bend (Figure 3).

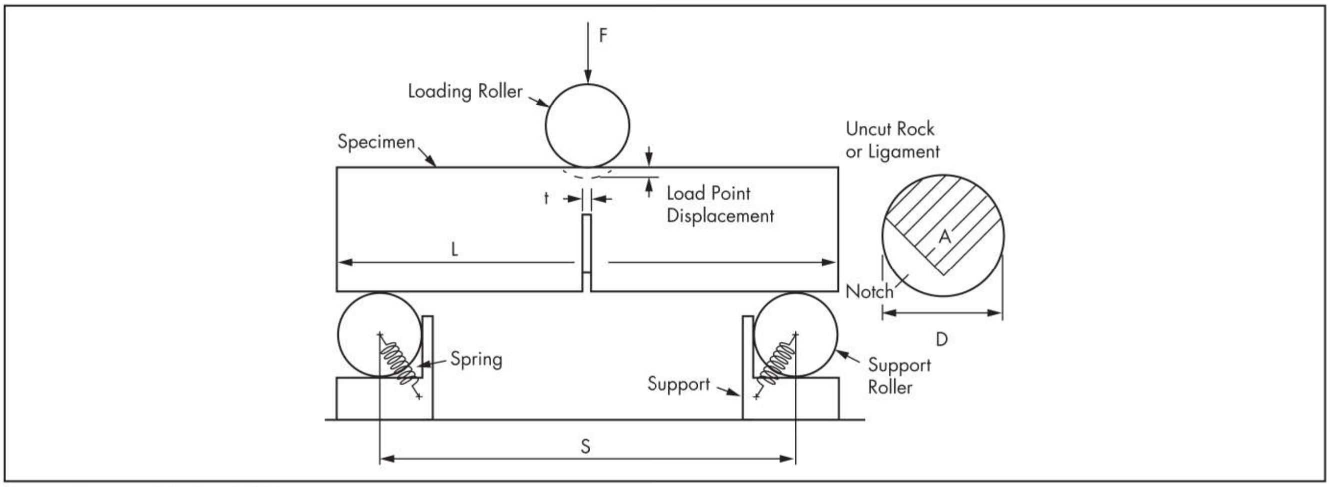
Details of the test methods can be found in Ulusay and Hudson (2007) and Ulusay (2014). All tests are designed to provide repeatable and consistent results, and in most instances, the choice of test will depend on the availability of the test and/or available sample size. As guidance, the

Table 4 General relationship between crushing resistance and a range of tests

Crushing Resistance	Fracture Toughness, MN/m$^{1.5}$	Brazilian Tensile Strength, MPa	Uniaxial Compressive Strength, MPa	Point-Load Is50, MPa	P-Wave Velocity, m/s	Crushing Work Index,* kW·h/t	Drop Weight, A × B
Minimal (1)	<0.25	<0.5	<5	<0.25	<500	<2	>127
Very low (2)	0.26–0.75	0.5–2.5	5–10	0.25–0.5	500–1,000	2–5	68–127
Low (3)	0.76–1.2	2.6–5	11–50	0.6–2	1,001–2,500	6–12	57–67
Moderate (4)	1.3–1.8	6–15	51–150	3–7	2,501–4,000	13–18	44–56
High (5)	1.9–2.6	16–23	151–250	8–12	4,001–5,000	19–25	39–43
Very high (6)	2.7–4.0	24–35	251–350	13–20	5,001–6,500	26–35	30–38
Extreme (7)	>4.0	>35	>350	>20	>6,500	>35	<30

Courtesy of Bear Rock Solutions Pty Ltd.

*The Schmidt hammer test is not included because of the range limit. Crushing Work Index values are only included for completeness. Crushing Work Index is known to generate highly variable results, and as such, values from these tests should not be relied on. Details and a critical review of the test can be found elsewhere in this handbook.



Source: Ulusay and Hudson 2007

Figure 2 Chevron bend fracture toughness

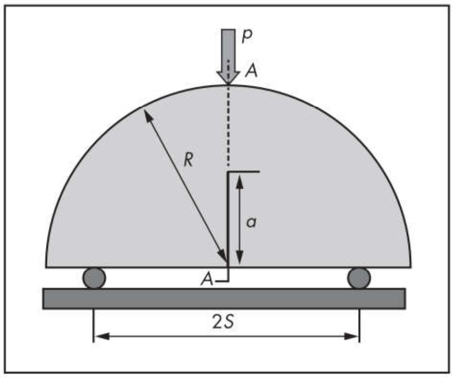
chevron bend uses sample lengths of four times the core diameter, whereas the semicircular bend uses 30-mm-thick discs cut from cores with 76-mm diameters. Fracture toughness has been cited by several authors over the last 20 years as having a close relationship to rock breakage behavior. Bearman et al. (1991) and Briggs et al. (1997) reported links to crushing and comminution, with the 1997 study showing a strong link to energy mapping approaches such as the JK drop weight test. As such, its application is beyond that of a mere index, and it should be considered as a parameter than can be used for quantifying crushing strength and machine performance.

ITS, also known as the Brazilian tensile strength test (Figure 4), was introduced because of the difficulty in undertaking a direct tensile test on rock materials. In the ITS method, there is no attempt to physically pull the sample apart; rather a disc of material is compressed to establish a stress regime that leads to a tensile failure being induced.

The ITS requires little sample preparation and limited core (sample discs need to be a minimum of 54-mm diameter but only require a disc thickness of ≥0.5 × diameter), so in this regard, the test has minimal requirements. The test is well established with high repeatability and typically low variability in results. Another advantage is that should enough sample be available, ITS samples can be tested in a variety of directions to determine the extent of any anisotropy in the samples. As a measure of *strength*, providing that the minimum requirements of the standards are followed, ITS shows less variability than the uniaxial compressive strength (UCS) and point-load strength tests, and it also displays improved repeatability. In addition, the ability to obtain many more ITS test discs from a given core length, compared to UCS, provides improved representivity. Given the various benefits of ITS, the use of this test should be preferred over UCS for geotechnical indexing tests for crushing.

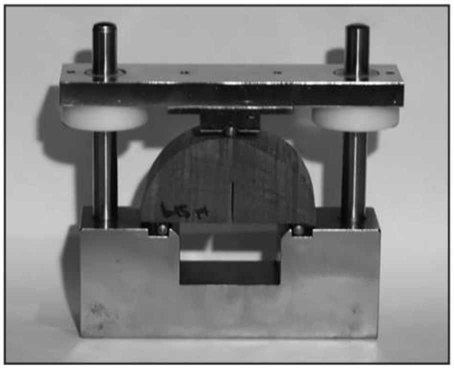
UCS and point-load testing (PLT) are often discussed together, as the point-load test was originally designed to be a rapid technique for determining UCS. UCS is a well-known test that relies on the compression of a cylinder of rock core, with the key dimensions being the diameter of the core and the length-to-diameter ratio.

The core is compressed axially (Figure 5), and the force at failure is recorded. The peak force divided by the cross-sectional area of the core gives the UCS for the sample. During the test, it is also possible to measure the Young's modulus of the rock by recording the displacement achieved during the test. Young's modulus is then calculated as the gradient of the stress-versus-strain graph from the test. There are a range of defined calculations for various forms of Young's



Source: Ulusay 2014

Schematic



Courtesy of Bear Rock Solutions Pty Ltd.

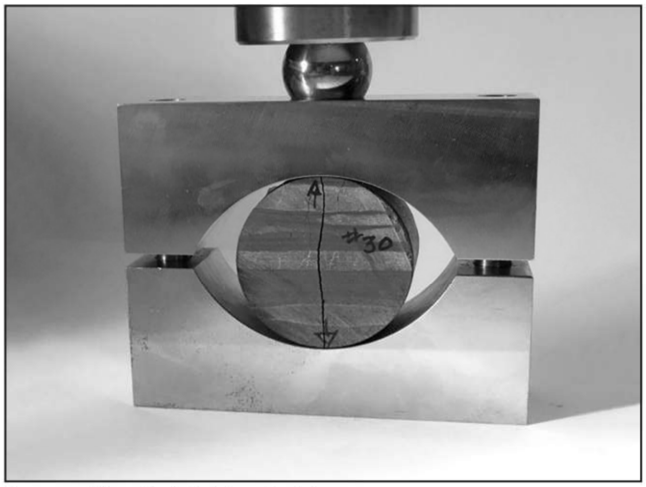
Test Piece

Figure 3 Semicircular bend fracture toughness test

modulus, and a discussion of these can be found in the ISRM publication by Ulusay and Hudson (2007). In an addition to the standard test, strain gauges can be attached to the rock sample to measure axial and lateral strain. Using this data, the Poisson ratio for the rock can be determined. Although sometimes quoted, the use of Poisson's ratio does not appear to be strongly correlated with crushing performance.

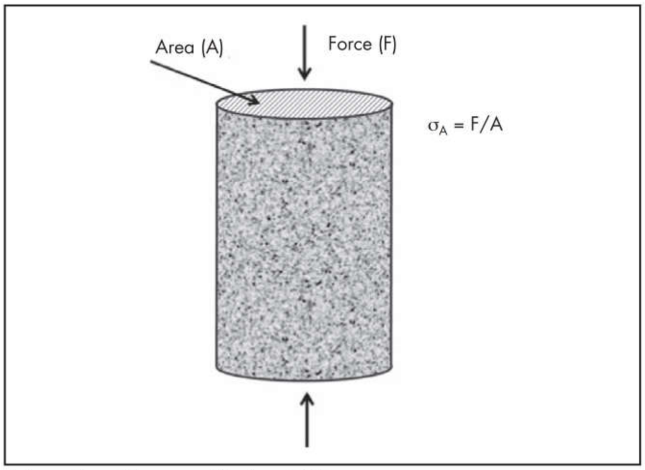
One of the drawbacks of the UCS test is the variability seen in the results, which is through samples fracturing under different modes of failure. The tests consume a large amount of core (length-to-diameter ratios of 2.5:1 as required by the ISRM and 2:1 to 2.5:1 as required by ASTM D7012-14e1), and if recommendations for load application rate and the end preparation of the cores are not closely followed, variability can become extreme. The consequence is that useful core is consumed, without any quality data being gained.

PLT was developed as a rapid and portable means for obtaining an estimate of UCS. The ability to undertake PLT in the field is a valuable feature, and it can provide information on general trends. As mentioned previously, variability can be an issue with UCS tests, and this is also observed in PLT. Depending on the test piece geometry, the variability can be higher than in UCS tests. PLT relies on the use of two diametrically opposed platens truncated by 5-mm-diameter points (Figure 6).



Courtesy of Bear Rock Solutions Pty Ltd.

Figure 4 Brazilian tensile strength test



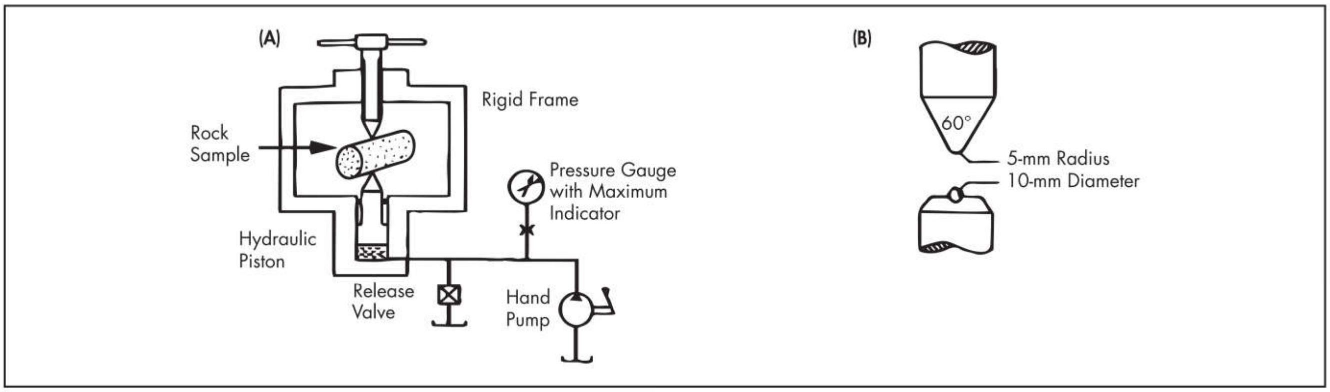
Adapted from Ulusay and Hudson 2007

Figure 5 Geometry for uniaxial compressive strength test

The rock sample is placed between the pointed platens, and a load is usually applied with a small portable pump, often of a manual, hand-operated type. The force at failure is used in a standard equation, and the force is then corrected to an equivalent for a 50-mm-diameter core. One advantage of PLT is that the test pieces can be of differing geometries, that is, diametric core, axial core, or irregular lumps. Although this is an advantage for the ability to gain a PLT value, the issue of variability again comes to the fore, with irregular geometry introducing extra variance. Another key parameter to consider regarding variability of results is the maintenance of the pointed platens. With use, the spherical truncations will wear, and this wear impacts the profile of the tips. As the spherical truncation is lost because of wear, the results from PLT will deviate from those expected.

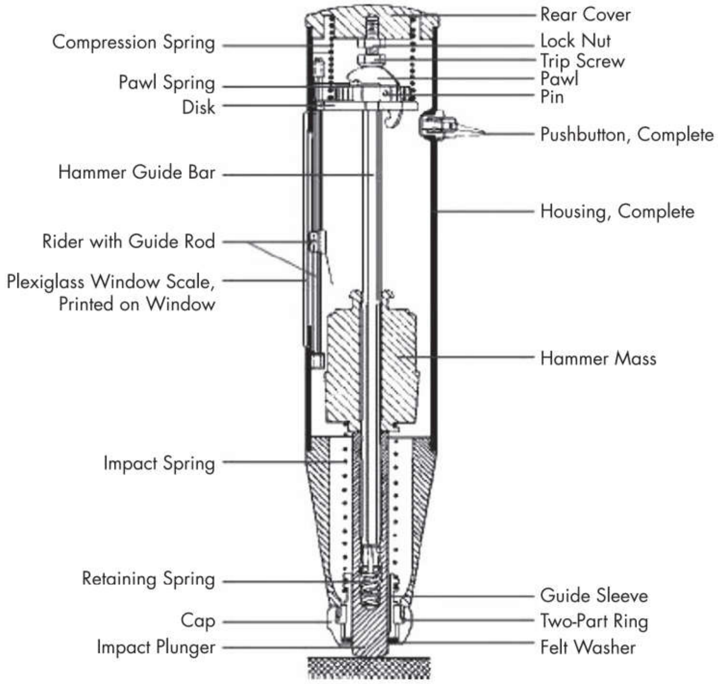
In summary, both UCS and PLT are useful indexing tests when used to examine trends, but because of issues around variability, some care must be exercised in the use of the results.

All the preceding tests are destructive; that is, the core material is fragmented at the end of the tests and is therefore



Source: Hudson 1993

Figure 6 Point-load strength test



Courtesy of Gardco

Figure 7 Schmidt hammer

not available for any subsequent testing. The geotechnical tests listed at the beginning of this section show two tests that are nondestructive in nature. One is the Schmidt rebound hammer and the other is the sonic velocity.

The Schmidt hammer test (Figure 7) was developed to provide a quick assessment of the strength of concrete blocks. The test has since been deployed as a measure of rock strength and has found acceptance as the quickest and easiest strength assessment technique. The test is covered by the ISRM standard (Ulusay 2014), and the following is a summary of the key points.

The test is based on a handheld unit that has a spring-loaded piston mechanism that is released when the plunger is pressed against the rock surface. The impact of the piston onto the plunger transfers energy to the rock. The rebound value is measured as the amount of energy recovered, which in turn relies on the hardness of the rock. The Schmidt hammer is available in two versions: the L-type and the N-type. The L-type has a lower impact energy and improved sensitivity in the lower ranges, making it better suited to weaker rock types, whereas the N-type has a higher energy and better deals with irregular surfaces. Various workers have provided equations to relate the rebound number to UCS. As a rapid and portable indexing tool, the Schmidt hammer is useful for identifying trends. The main factors to consider are the calibration of the hammer, the flatness of the surface, significant strength differences between the grains or crystals and the matrix, weathering and moisture content plus the presence of anisotropy, and the confinement of the rock under test. Any spring-loaded device will eventually require maintenance to address loss of elasticity from extended periods of use, and hence any unit used must be regularly checked. In addition, the point on the rock surface where the unit is applied must be flat, otherwise there may be some localized crushing or slippage. The final point relates to the stability of the sample under test. If used on a large stable rock, then this is not a concern, but where the unit is applied to a block of rock or a core, then it is essential that the sample is firmly secured to prevent movement and hence an invalid reading. As a general rule, the range of application for the Schmidt hammer is mostly accepted to be in the 20–150 MPa UCS range. Outside of this range, sensitivity or data scatter issues may be encountered.

The other main, nondestructive test available is the sonic velocity test. In this test, the aim is to measure the P- (primary, longitudinal) and S- (secondary, traverse) wave velocities along the length of the sample. The measurement is achieved by measuring the transit time of the waves and dividing by the length of the sample. ISRM (Ulusay 2014) provides full details of the test procedures required. In a laboratory setting, the sample is mostly intact core, but blocks and discs can be used, providing the dimensions meet the requirements of the standard. Using the data generated and the density of the sample, it is also possible to calculate elastic properties, including dynamic Young's modulus and Poisson's ratio. P-wave velocity is most often used to provide a measure of the rock integrity and competence. In general terms, there is a trend between P-wave velocity and strength tests.

Table 5 Typical Bond abrasion index values

Sample Type	Bond Abrasion Index	Classification
Bauxite	0.0005–0.02	Nonabrasive
Pisolitic iron ore	0.005–0.03	Nonabrasive
Dolomite	0.01–0.05	Nonabrasive
Magnetite	0.1–0.3	Slightly abrasive–abrasive
Marra Mamba iron ore	0.2–0.3	Slightly abrasive–abrasive
Basalt	0.2–0.4	Slightly abrasive–abrasive
Diabase	0.2–0.4	Slightly abrasive–abrasive
Gabbro	0.4	Slightly abrasive–abrasive
Amphibolite	0.2–0.45	Slightly abrasive–highly abrasive
Copper ore	0.3 –0.45	Abrasive–highly abrasive
Andesite	0.4–0.5	Highly abrasive
Graywacke	0.3–0.6	Highly abrasive
Lamproite	0.35–0.6	Highly abrasive
Gneiss	0.4–0.6	Highly abrasive
Granite	0.45–0.65	Highly abrasive–extremely abrasive
Hornfels	0.4–0.7	Highly abrasive–extremely abrasive
High-grade hematite	0.8–0.8	Abrasive–extremely abrasive
Diorite	0.4–0.8	Highly abrasive–extremely abrasive
Quartzite	0.7–0.9	Highly abrasive–extremely abrasive

Ore Abrasivity

The abrasivity of the feed material is the ability of the feed to wear the components of the crusher. Many types of wear test exist, and as they relate to milling, there are other mentions in this handbook. For crushers, the ones of interest are those that examine loss of metal because of a certain form of wear. The most widely known test is the Bond abrasion index, where a prescribed charge of feed of a specified fraction is placed in a rotating drum. A paddle within the drum rotates through the mass. The mass of metal lost from the paddle after a given time is then stated as the abrasion index. This test was introduced in the late 1940s and is still in widespread use. This test predominantly examines flow abrasion, that is, low normal force wear caused by differential speed and abrasion. Table 5 gives a summary of Bond abrasion data.

In crushers, such wear occurs, but not at the point where the rocks are nipped and broken. At these points, the wear is enhanced because of the high normal force gouging abrasion. Tests for this type of wear are less well known, and they generally lack an inherent link to actual wear rates in crushers; that is, results are indicative of the magnitude of the wear rates, not explicit to a direct metal loss. The two tests of interest in this area are the gouging abrasion and the Laboratoire du Center d' Études et Recherches des Charbonnages de France (CERCHAR) tests. The gouging abrasion test is a recent development (Figure 8) and relies on sweeping a test piece of the metallic test material across the face of a prepared rock sample.

The metallic test piece is mounted on a sturdy pendulum device, usually a modified Charpy or Izod test machine, and the rock sample is located at the base of the pendulum arc. The pendulum and metallic test piece therefore swings from a given height and gouges a path along the surface of the rock sample. The index is calculated from the dimension of the wear-flat surface on the end of the metallic test piece. In this regard, the test replicates a high normal force plowing or gouging wear regime. As a guide, Table 6 provides measured values for the gouging abrasion index.

The CERCHAR test is a more established test and has been standardized by ISRM (Ulusay 2014). Figure 9 shows the equipment.

In this test, a weighted metallic needle is moved across the flat surface of a prepared rock sample. The CERCHAR abrasion index is calculated from the diameter of the wear-flat surface of the needle. In this instance, the weighted needle does not exert a high force onto the rock surface, so in essence, the wear regime is a low normal force, abrasion-type test. There is little or no gouging involved. Table 7 provides a guide to the classification of wear from the CERCHAR test.

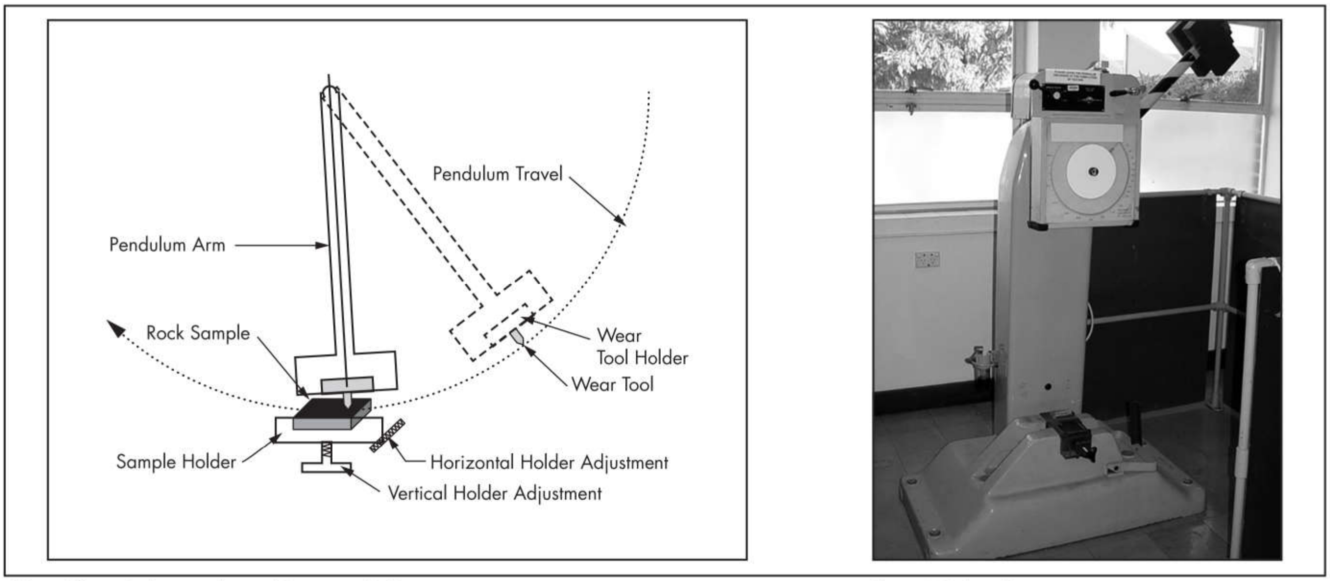
Feed Conditions

Crushers are particularly susceptible to feed conditions, and these play a major part in the optimization of crusher performance. The main factors relating to feed include

- Feed size distribution,
- Feed rate,
- Distribution of feed around the chamber,
- Sized-based segregation of feed, and
- Presence of clay and/or moisture.

The impact of the preceding factors will vary depending on the type of crusher. One often-cited issue is that of choke feeding in cone crushers. For more details on this and related issues, see Chapter 3.4, "Gyratory and Cone Crushers."

Process control of crushers needs to take into account many of the factors examined in the previous section. Because of the lack of crusher variables that can be rapidly adjusted, most control has focused on keeping the crusher running at



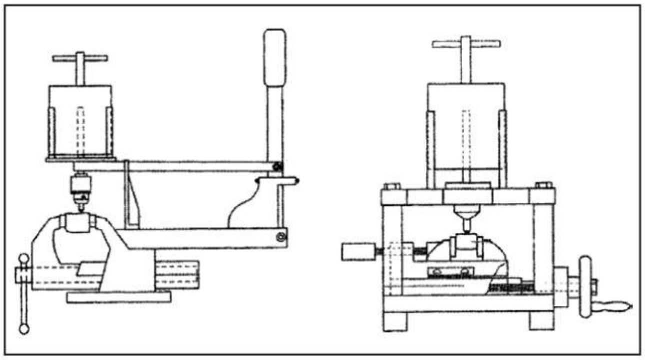
Adapted from Golovanevskiy and Bearman 2008

Photo © Richard Bearman

Figure 8 Gouging abrasion index equipment

Table 6 Typical gouging abrasion index results

Sample Type	Gouging Abrasion Index	Classification
Basalt (weathered)	0.50–1.00	Nonabrasive
Bauxite	2.90–6.90	Nonabrasive–slightly abrasive
Pisolitic iron ore	4.50–9.00	Nonabrasive–moderately abrasive
Basalt	8.30–18.80	Moderately abrasive–highly abrasive
Breccia	16.90–18.00	Highly abrasive
Copper porphyry	16.00–18.00	Highly abrasive
Banded iron formation	16.10–19.80	Highly abrasive
Quartzite	18.20–22.20	Extremely abrasive



Source: Ulusay 2014

Figure 9 CERCHAR test equipment

Table 7 Typical CERCHAR results

CERCHAR Abrasion Index	Classification
0.1–0.4	Extremely low
0.5–0.9	Very low
1.0–1.9	Low
2.0–2.9	Medium
3.0–3.9	High
4.0–4.9	Very high
>5.0	Extremely high

maximum power to deliver full size reduction, or to keep the crusher at a given discharge setting to generate a specified size.

All manufacturers provide process control systems that can target power or CSS, and within these targets, there is also a compensation for liner wear. Often tied to these systems is instrumentation to detect the level of feed both in the feed bin and in the crushing chamber and feedback loops to control the speed of the crusher feeder.

As part of the process control system for most crushers, power, hydraulic pressure (where applicable), motor temperature, lubricating oil flow rate, lubricating oil in and out temperature, countershaft speed, rotor speed, discharge setting, mainshaft position (where applicable), and feed level and rate are all monitored. To control the crusher, the only control variables readily available are discharge setting, rotor speed (impact crushers), and feed rate. Having such a limited set of control variables constrains the speed and flexibility of control, particularly when it must be remembered that in the case of cone crushers, the discharge setting is usually altered by stopping feed to the crusher.

As mentioned, most crusher suppliers provide control systems to varying levels of sophistication. One of the systems with the longest pedigree is the automated setting regulation (ASR) package for cone crushers provided by Sandvik, with the original system dating back to the Svedala company. In the current configuration, the system is now known as ASRi, where "i" denotes the move to what Sandvik terms an *intelligent* version. In essence, the ASRi system has three operating modes:

1. Auto-CSS—the ASRi system aims to maintain the desired CSS.

2. Multi-CSS—two different product curves can be combined to give a new desired product.
3. Auto-load—the ASRi system regulates the setting so that the crusher operates at a desired load level.

In the Sandvik head-adjusted cone crushers, the system monitors a range of operational parameters including power, hydraulic shaft adjustment pressure, and CSS. Depending on the mode selected, the system will control CSS (auto-CSS and multi-CSS) or it will target a power limit (auto-load). The system is designed to have a user-friendly front-end display and to communicate with wider plant control systems.

The display seen in Figure 10 shows one of the main trends in control interfaces in process plants, with the move to a clean, visual display with a *dashboard* approach, whereby only the important information is shown, which is graphically represented in a form that can be quickly interpreted by the operator.

It has long been known that the eccentric speed in cone crushers has the potential to be used for process control, but because of the cost and durability of older variable-speed drives, there was a reluctance to study this aspect further. In recent years, work at Chalmers University and Metso has examined the use of modern variable-speed drives and concluded that the use of speed can help extend liner life and the generation of targeted product sizes.

Modeling and Simulation

Modeling and simulation of crushers and crushing circuits can be undertaken at a variety of levels:

- Basic uses hard-wired or look-up tables to estimate throughput and size reduction.
- Intermediate is classification-function based and uses mechanistic models.
- Numerical is based on discrete element modeling (DEM) to model the action of individual particles.

At the basic level, there is a range of software options available that provide good representations of crushing and screening circuits and will ensure that the flow within the circuits converge and give a mass balance. These packages tend to use either manufacturer data or simple models to provide the user with estimates of unit and circuit performance.

Intermediate modeling uses sophisticated flow-sheet simulation packages, such as JKSimMet and SysCAD, and can use various types of crusher models:

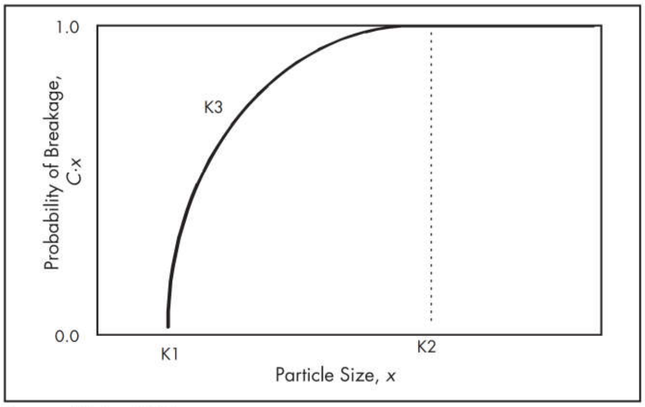
- Classification function models based on fitted or empirical relationships for crusher parameters
- Mechanistic crusher models based on direct mechanical crusher design parameters

Both of the preceding approaches use detailed experimental descriptions of breakage, that is, appearance function, to describe the breakage in the crusher.

One such example of the classification function approach is the well-documented Whiten crusher model that uses classification parameters K1, K2, and K3 to describe the workings of the crusher and the JK drop weight breakage function to describe the response of the rock. The model framework can be applied to a wide range of crusher types. The K1 and K2 parameters are not inherent crusher parameters, but rather they can be fitted via relationships with operational factors such as F80 or throughput. Models such as the Whiten model are well regarded and often used where performance data for the crushers are available. If a particle is smaller than a certain size (K1), it will fall through the crusher and become product. If it is larger than a certain size (K2), it cannot fall through the crusher but will fall through until it is caught. A typical classification curve is shown in Figure 11.

Courtesy of Sandvik

Figure 10 Interface for the ASRi control system



Source: Whiten 1984

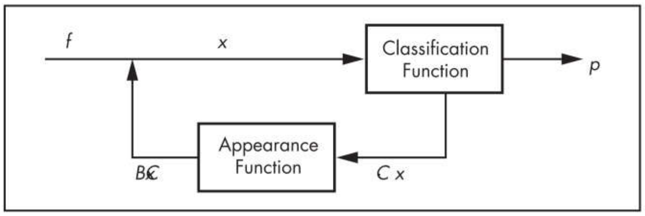
Figure 11 Classification function for the Whiten crusher model

In the Whiten model, a power curve with exponent K3 is used to join the two defined points. For many types of crusher, $2 < K3 < 2.5$ is a good description.

In the case of a cone crusher, K1 represents the CSS, and K2 the open side setting (OSS). This assignment of K1 and K2 to CSS and OSS is, however, not definitive, and in many instances, the K parameters need to be fitted.

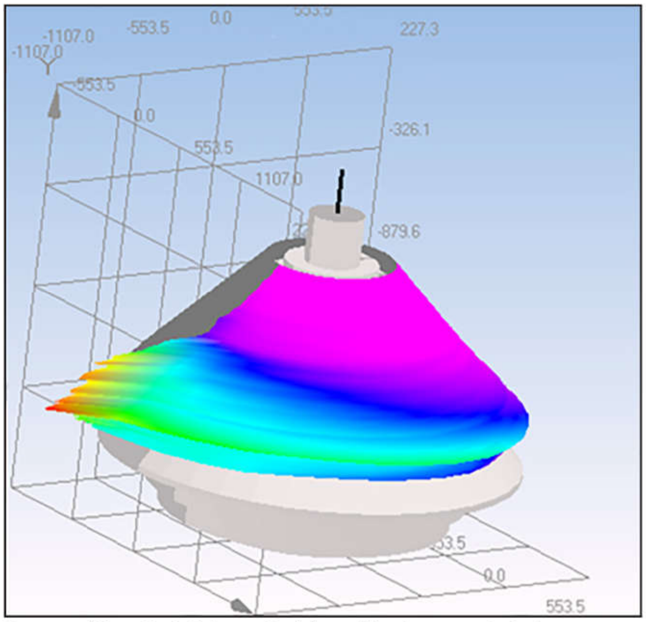
To model the breakage process, the Whiten model uses a set of curves (cubic splines) to describe the size distribution produced by breakage events of increasing size reduction or energy input. This defines the breakage function for the feed material.

The classification and breakage functions are combined to allow the model to classify the output of the breakage function and to ensure that the mass balance is correct. The function of the model is shown in Figure 12.



Source: Whiten 1984

Figure 12 Schematic of Whiten crusher model



Courtesy of Bear Rock Solutions Pty Ltd. and Met Dynamics Pty Ltd.

Figure 13 Three-dimensional plot of power consumed in cone crushing

Mass balance equations may be written about each node as

$$x = f + B \cdot C \cdot x \qquad x = p + C \cdot x$$

where

x, f, and p = vectors representing the amount in each size fraction in the crusher feed and product, respectively

B = breakage distribution function, a lower triangular matrix giving the relative distribution of each size fraction after breakage

C = classification function, a diagonal matrix describing the proportion of particles in each size interval entering the crushing zone

Combining the mass balance equations gives

$$p = (I - C) \cdot (I - B \cdot C) - 1 \cdot f$$

Therefore, from B and C, it is possible to calculate the product size distribution (p) for any feed size distribution (f).

Mechanistic models take the ideas from the intermediate approach and increase the functionality by removing the need for fitting of parameters. In crushing, mechanistic models have been developed for a variety of machines including secondary sizers, VSIs, primary gyratory crushers, and cone crushers, with the latter two attracting the most attention. In the mechanistic approach, the geometry and mechanics of the crushers are used to generate the energy application within the crusher, and then, this is coupled to a representation of breakage. In some cases, the breakage functions can be the same as those used in the intermediate approach. The advantages offered by the mechanistic approach are as follows:

- They can run as stand-alone models or within a flowsheet simulation.
- Operational data is not required to set up the model.
- They incorporate actual components and dimensions specific to the crusher.
- They track size classes of particles through the crushers and develop energy profiles that can be used for prediction of power, crushing force, liner wear, size reduction, and throughput.
- They can be used to model wear of liners and therefore can be used to track changes in performance with wear.

Mechanistic crusher models are well covered in work from Bearman et al. (2011) for a kinematic crusher model for primary gyratory and cone crushers, Evertsson (2000), Hulthén (2010) for cone crushers, Nikolov (2002) for impact crushers, and Heng et al. (2003) for sizers.

A feature of all mechanistic models is that they couple the crusher chamber geometry with equations of particle motion and a population balance breakage model so that they are not crusher specific.

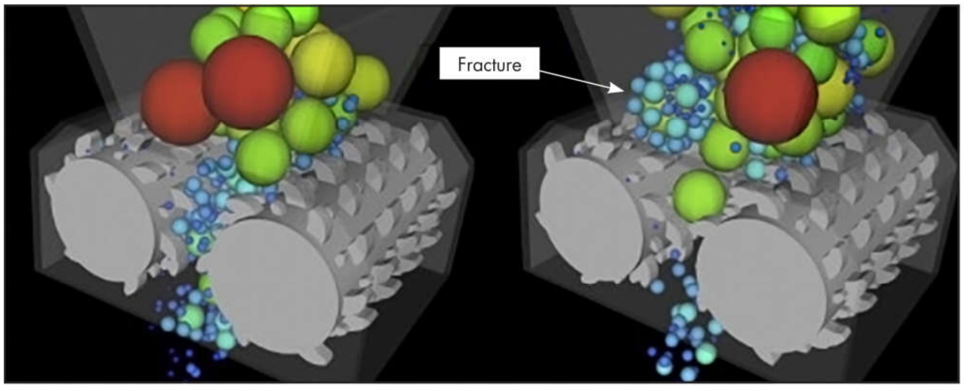
Using the preceding approach, the models are able to predict a range of critical parameters, such as the following for cone crushers:

- Product size distribution
- Power consumption
- Energy distribution in the chamber
- Hydraulic pressure
- Onset of packing and power overload

The models generate a variety of key process and mechanical diagnostic parameters (Figure 13) for use in the analysis. In combination, these provide a unique view of the crusher application.

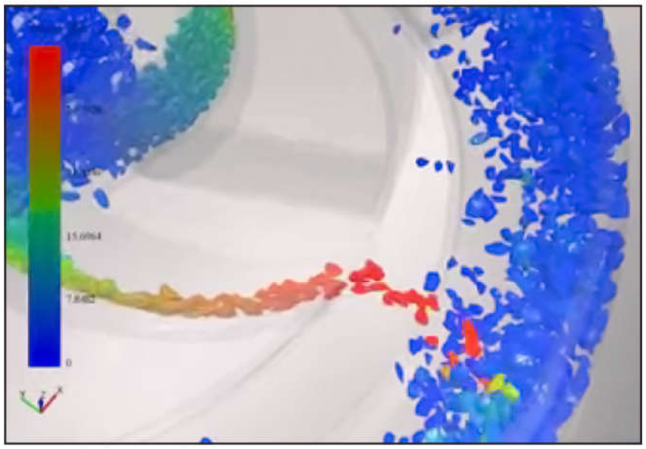
Unlike the basic and intermediate approaches detailed previously, numerically based techniques are not currently suited to use in a circuit simulation setting because of the computational requirements. However, the application of numerical techniques to crushers has increased dramatically because of the rapid increase in computing power. In these models, each particle is represented by either an individual element or a group of elements within the computing code. All collisions, interactions, and movements are based on physics models, and the crusher itself is defined via engineering drawings. Various DEM codes have been used to examine crushers of different types, including gyratory, cone, sizers, double-roll (Figure 14), and impact crushers (Figure 15).

The main drawbacks have been computational power and speed and also the ability to reach small particle sizes. A thorough review of DEM in comminution is provided by



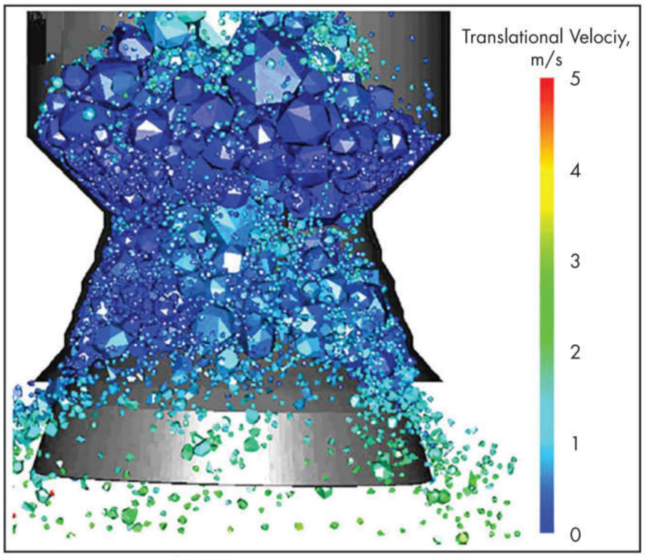
Source: Cleary and Sinnott 2015

Figure 14 Double-roll crushers



Source: Chalmers Rock Processing Systems 2015

Figure 15 DEM simulation of a VSI crusher (plan view)



Source: Popatov et al. 2007

Figure 16 Fast breakage model of an HP100 cone crusher

Weerasekara et al. (2013), and in this, the methods applied and the steps taken to overcome issues are well described.

In an effort to deal with some of the main issues associated with DEM, Metso developed its proprietary fast breakage approach (Potapov et al. 2007), which combines DEM with population balance modeling. This allows the modeling of finer size fractions, without the need to specifically model each grain as a discrete particle. An example of the output is shown in Figure 16.

The power of a system such as DEM, or a derivative, is obvious, as it deals with all aspects of the crusher simulation. Currently, however, the application is restricted to stand-alone engineering studies. With increases in computational power, this situation will undoubtedly change over the course of the coming years, and this will allow wider application and the eventual use within a full flow-sheet simulation environment.

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