Quarry products, such as construction aggregate, are produced in a multi-stage processing operation that involves drilling and blasting, extraction, crushing and milling, screening and classification. Ideally, all material extracted from the ground is a useful product. However on average only 60 to 80% finds a commercial use. Efficient operation of the quarry processes helps to minimise the amount of quarry fines and waste produced.

This section is an output of the MIST Quarry Fines Minimisation' and Waterless Fines Removal' projects. These were co-ordinated by the British Geological Survey (BGS); the project team included Green Horizons Environmental Consultants and Camborne School of Mines. The project steering panel included Aggregate Industries, Bradley Pulverizer, Metso Minerals, QPA and Tarmac. Many of these project partners have also contributed material in the form of comments, images and case studies.

Introduction

Production and process technologies are a key aspect of any aggregate operation. The type of equipment and process configuration used is largely dependent upon the local market for construction materials, company experience and preferences, acceptance of new ideas and attitudes towards capital investment, the legacy of past production (especially in older operations) and the nature and geology of the mineral exploited. The responsibility for producing aggregate from as quarried mineral usually falls to a site production or quarry manager; these and students of quarry management will be the primary user of information in this section of Goodquarry.com.

Primary aggregates are produced from two main types of quarrying operation, crushed rock (Photo 1) and sand and gravel (Photo 2). Crushed rock aggregate is produced from hard, strong rock formations including igneous (andesite, basalt, diorite, dolerite, gabbro, granite, rhyolite, tuff), metamorphic (hornfels, gneiss, quartzite, schist) and sedimentary (sandstone, limestone) rock. It is produced from quarries that are much larger and deeper than sand and gravel pits, and involve large investments with quarry outputs that are typically in the range 100 000 to 5 million tonnes per annum (tpa). Sand and gravel is produced from naturally occurring deposits derived from the erosion of particles that were transported and deposited by water, wind or ice. Sand and gravel pits are usually shallow, sometimes only five or six metres deep. Operations are likely to be shorter term than for crushed rock and, with progressive restoration normally following closely behind extraction, the working area at any given time is usually comparatively small. They typically produce 10 000 to 1 million tonnes per annum (tpa), with most in the range 100 000 to 300 000 tpa.

Primary aggregate is produced by extraction and processing; most extracted mineral cannot be used as dug and processing prepares it to be used as a construction material. Extraction, also known as quarrying, involves removing mineral from the ground and delivering it to a production plant in a form suitable for processing. Processing is typically carried out in a production plant and involves crushing, milling and screening. The key parameters for aggregates are particle size and distribution, particle shape, physical and mechanical properties and lack of contaminants.


Photo 1. Panorama of limestone quarry


Photo 2. Sand and gravel washing plant

The information presented in Production and Process Technology is split into six sections:

- Aggregate production summary this gives a brief explanation of aggregate production, products, and quarry fines and waste;
- Production good practice this outlines good practice for the operation of quarry

crushing and washing equipment, with an emphasis on quarry fines minimisation;

- Technology: extraction and crushing this gives an explanation of the processes and technology involved in extraction and crushing of aggregate;
- Technology: washing plant this gives an explanation of the processes and technology involved in washing aggregate;
- Technology: dry processing this gives an explanation of the processes and technology involved in drying, air classification and screening of aggregate;
- Future technology and practices this is a forward look at the issues that will drive developments in aggregate production technology and processes.

Aggregate Production Overview

Extraction

Extraction is the removal of mineral from the ground and its transfer to a processing plant (which may be at a fixed location or present as a mobile plant in the quarry workings). The four basic operations of extraction include overburden removal, drilling and blasting, secondary fragmentation, and digging, loading and hauling.

The methods and equipment used depend primarily on the type of deposit and source rock being worked. The key factor is the degree of consolidation of the deposit, but other considerations include the physical properties of the rock (density, impact strength and abrasiveness) and the rate and scale of production required.

Production plant processing

Production of hard rock aggregate involves screening (scalping) to remove fines and waste material followed by crushing and screening to produce material with specified size grades (Animation 1 and Fig. 3). Crushing is carried out to reduce the size of the as quarried mineral from large blocks (up to a metre across) to a size finer than 20 to 50 mm. This size reduction is carried out in stages, typically with a low size reduction ratio (<6:1) and is characterised by the use of certain types of crushing equipment, as shown in Table 1:

Production Technology — Table 1

Quarry process plant crushing stages: typical equipment and products

Crushing stage	Crushing equipment	Maximum feed size (mm)	Maximum crushed product size (mm)
Primary	Jaw crusher Gyratory crusher	700-1000	100-300
Secondary	Cone crusher HSI crusher Jaw crusher (rarely)	100-250	20-100
Tertiary	Cone crusher VSI crusher	14-100	10-50
Quaternary (& subsequent stages)	VSI crusher Cone crusher	10-40	10-20

The particle size of the crushing product will determine the yield of the saleable product. The particle shape requirements of the products and the rock type will affect the type and range of plant used. For further details click here.

Animation 1. Quarry process line

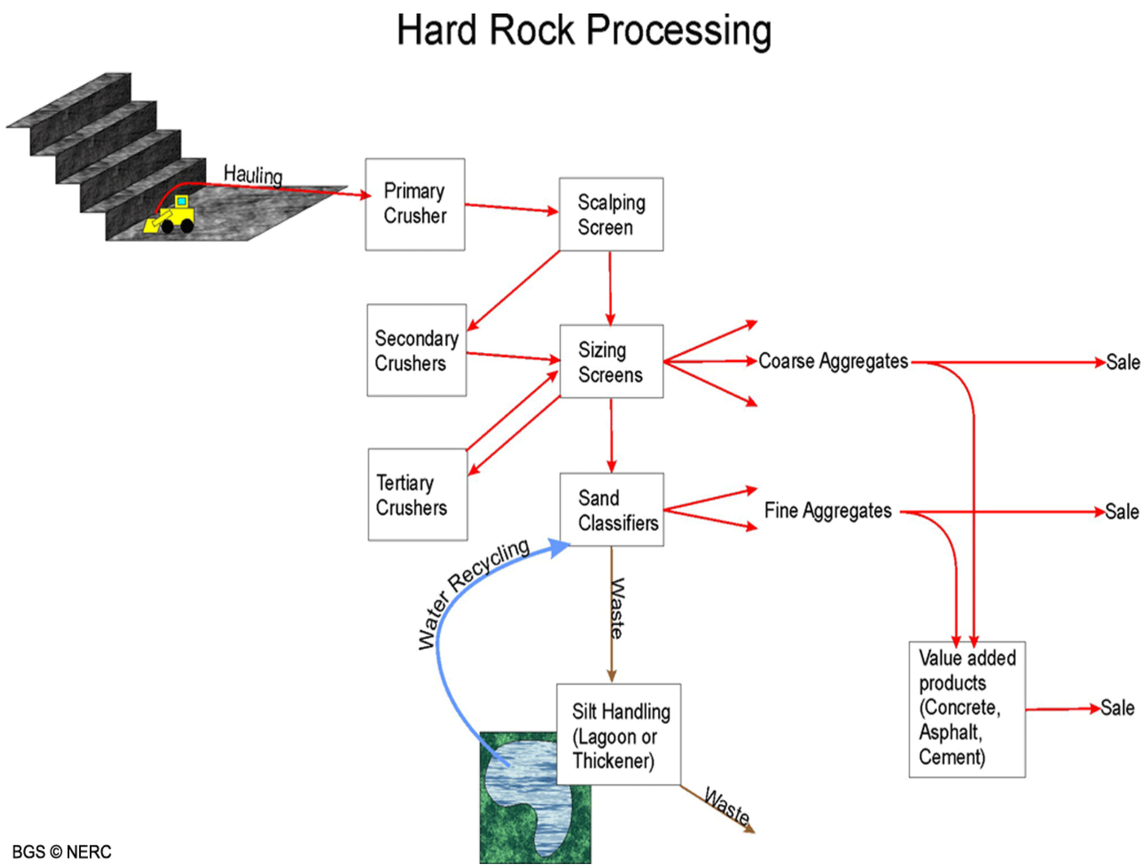

Figure 3. Hard rock processing

Production of sand and gravel involves washing and scrubbing to remove clay, separation of the sand fraction by screening, grading of the gravel, sand classification and dewatering, and crushing of any oversize gravel to produce a saleable product (Photo 4). Washing removes silt and clay (material finer than 0.063mm), which is present either as surface coatings or as clay-bound agglomerates that need to be broken down. The silt and clay content of a sand and gravel deposit is an important parameter in determining its economic viability; the silt content should be lower than 25% and the clay should be much lower as it is harder to remove. Some gravels containing clay (hoggin) may be sold "as dug" for constructional fill. The silt and clay is removed using cyclones and settled out in lagoons, from which process water is recovered. Dry screening is also used to produce building sand at some locations. Blending of sands from the same or different sites can be carried out to meet consumer particle-size requirements; this also enables maximum use of the mineral resource. Washing plants are being built at some hard rock quarries to upgrade the quality of the scalpings and fines. For further details click here.

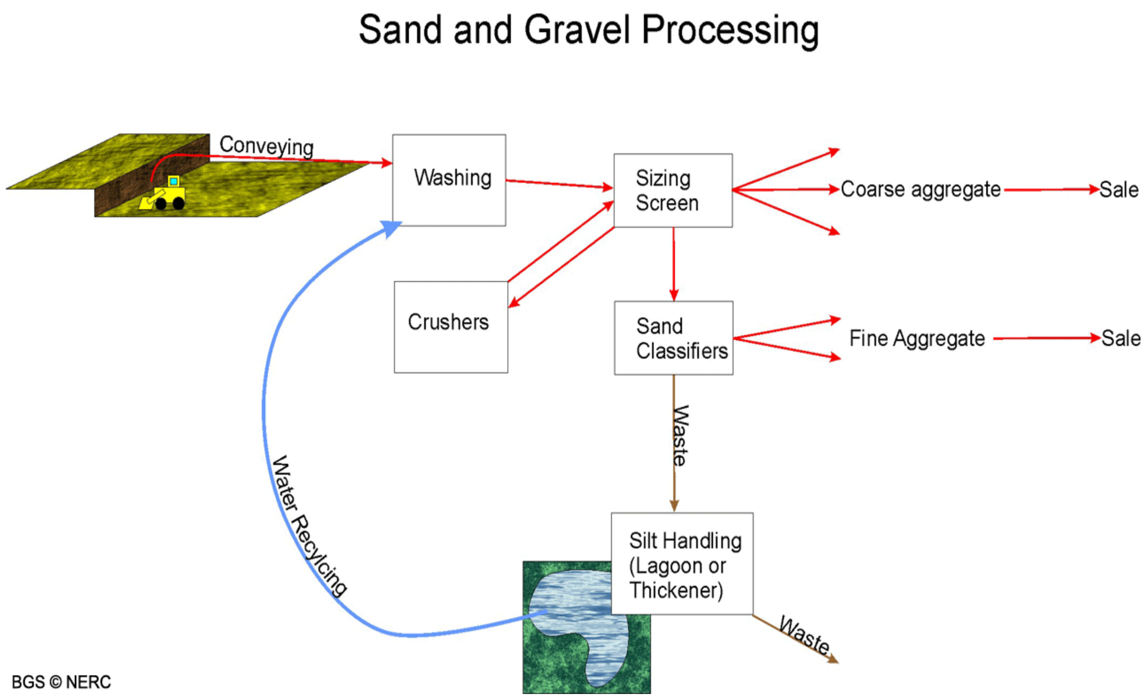

Figure 4. Sand and gravel processing

Products

Products from quarries include aggregate, asphalt, industrial minerals, lime (agricultural and industrial), mortar and ready mixed concrete. Aggregates are the primary output from quarries in the UK; they are an end product in themselves and are used as the raw material in the manufacture of other construction products such as ready-mixed concrete, asphalt, lime and mortar. Crushed rock sands may also be produced; often referred to as manufactured sand. Aggregates are used in road construction, as railway ballast, in private housing, public infrastructure and industrial construction. A factsheet on aggregate supply in the UK is available to download from: www.mineralsuk.com/britmin/mpfaggregates.pdf.

The quality of quarry products used in the UK is controlled by the European Standards for Aggregates for concrete, mortar, asphalt and road construction. Information on these standards is available from the QPA website: www.qpa.org/prod_agg01.htm. The introduction of these European standards in 2004 raised the possibility that production practice may have to be modified. However, it is apparent from discussions with the UK quarrying industry that few alterations to their existing production practices have been required. The main changes were to product designations and the range of test sieves used in the quality control laboratories. Largely, existing products were accommodated by the new standards with minor process changes such as the size of screen apertures used; to some extent the new standards allow the industry greater flexibility and options in production of saleable aggregate.

Quarry products are defined by their particle-size grading; the product designations are based on the respective lower (d) and upper (D) sieve sizes, which are expressed as d/D. All-in products are essentially ungraded, crushed material. The exception is light gradings of armourstone which are specified in weight (kg). The following are the current product size designations (BS EN 12620 for concrete aggregate, BS EN 13043 for asphalt aggregate, BS EN 13242 for road construction, BS EN 13383 for armourstone and BS EN 13450 for railway ballast), with their equivalent designations in the older British Standards (BS 882 for concrete aggregate and BS 63 for asphalt aggregate) and Network Rail's specification for railway ballast in brackets:

- *Armourstone*

  Coarse gradings: 45/125, 63/180, 90/250, 45/180 and 90/180

  Light gradings: 5 to 40 kg, 40 to 200 kg, 10 to 60 kg, 60 to 300 kg and 15 to 300 kg

- *Graded products*
  4/40 (40 to 5 mm graded), 4/20 (20 to 5 mm graded) and 2/14 (14 to 5 mm graded)

- *Railway ballast*
  31.5/50 (28 to 50 mm railway ballast) and 31.5/63 (not used in UK)

- *Single sized aggregate*
  20/40 (40 mm single sized), 20/31.5 (28 mm single sized), 14/20 or 10/20 (20 mm single sized depending on end-use), 8/14 or 6.3/14 (14 mm single sized depending on end-use), 6.3/10 & 4/10 (10 mm single sized depending on end-use), 2.8/6.3 or 2/6.3 (6 mm single sized depending on end-use) and 2/4, 1/4 or 1/3 (3 mm single sized depending on end-use)

- *All-in aggregate*
  0/40 (40mm all-in), 0/20 (20mm all-in), 0/10 (10 mm all-in) and 0/6.3 (5 mm all-in)

- *Sand products / Fine aggregate*
  0/4 (coarse sand), 0/4 or 0/2 (medium sand depending on end-use) and 0/2 or 0/1 (fine sand depending on end use)

Products are typically stored in stockpiles (open air or covered), product bays, bins or silos (Photos 5, 6 & 7).

Photo 5. Limestone aggregate stockpile


Photo 6. Washed gravel

Photo 7. Washed concrete gravel

Quarry fines and waste

The production of crushed rock aggregate will produce a certain proportion of quarry waste, including quarry fines (<4 mm). The amount of waste is governed by the geology, nature of the rock, product specifications, extraction and production processes, and to some extent its location with respect to potential markets and market economics.

Quarry wastes are produced from overburden/ interburden materials, from washing of sand and gravel to remove fines, and from scalping, crushing and dry screening. Quarry wastes are largely localised at the sites where the mineral is worked. It can comprise up to 15 to 20% of the excavated rock; at some sites it may exceed 50% of the excavated rock after processing.

Quarry fines and scalpings can be difficult to sell and may become a waste product. They may be considered a resource (some scalpings are clean enough to meet Type 1 sub-base specifications and all waste has the potential to be used as low grade, low value constructional fill), although some can only be sold after additional processing. For further details click here.

Production Good Practice

Crushing plant

Ideally, a quarry will sell everything that is extracted and processed. In the past, quarries produced a range of single-size aggregate products up to 40 mm in size. However, the trend for highly specified aggregate has meant that products have become increasingly finer. Currently, many quarries do not produce significant quantities of aggregate coarser than 20 mm; it is not unusual for material coarser than 10 mm to be stockpiled and recrushed on demand. Decreasing the top size of aggregate produced has had an inverse effect on the proportion of fines produced; a 40 mm top size results in 5-10% fines, 20 mm top size results in 15-20% fines and 10 mm top size results in 35-40% fines. This represents up to an eight-fold increase in fines production.

The amount of fines produced increases as material progresses from primary to secondary and subsequent stages. The amount of fines arising from the primary crushing stage is strongly influenced by the blasting process; if rock can be removed without blasting this will reduce the amount of fines produced. The amount of fines generated during blasting may be as high as 20%. Table 2 indicates the fines content generated at each stage of the crushing process; the proportion of fines produced varies with the type of rock and also the type of crusher used.

Production Technology — Table 2

Quarry fines produced in hard rock aggregate operations

Production Stage	Rock type	Proportion of fines in the crusher product (weight %)
Primary crushing	Igneous + Metamorphic Limestone Sandstone	3 - 6% (Jaw) to 10 - 15% (Gyratory) 6 - 7% (Jaw) to 20% (Impact) 1 - 2% (Jaw) to 15 - 20% (Jaw & Gyratory)
Secondary crushing	Igneous + Metamorphic Limestone Sandstone	0 - 23% (Cone) 15 - 25% (Cone) to <30% (Impact) 10 - 15% (Cone)
Tertiary crushing (and subsequent stages)	Igneous + Metamorphic Limestone Sandstone	5 - 30% (Cone) to 40% (Impact) <20% (Impact) to 40% (Hammer mill) ~15% (Cone) to 40% (Impact)

NB Fines = quarry fines; the proportion of quarry fines produced is attributed to specific crushers (given in brackets after the figure)

Jaw crusher good practice

Overview

A jaw crusher consists of two metal plates that crush material as they close together (for further details on jaw crushers click here). As a compression crusher, they generally produce the coarsest material; this is due to the preferential breakage of rocks along inherent lines of weakness. Jaw crushers are mainly used in primary crushing as a means of preparing rock for subsequent processing stages; they are rarely used as secondary crushers (where they are used to boost primary production capacity). Some sand and gravel plants use granulators (a squat form of jaw crusher) for crushing cobbles (Figs. 8, 9 & Photo 10).

Jaw crushers do not produce a large proportion of quarry fines (material <4 mm) material; at a closed side setting (CSS) of 40 mm a jaw crusher will produce less than 10% of quarry fines and at a CSS of 200 mm it produces less than 1%.

Key finding

Jaw crushers are mainly used in primary crushing where the amount of fines produced is typically less than 5%; any attempts to minimise fines production at this stage will have little effect on the total fines arising as most are produced in the secondary and tertiary stages.

Feed

Jaw crushers are routinely choke fed as this maximises production capacity and ensures that particles are uniformly broken. It promotes stone-on-stone crushing which breaks up flaky or slabby particles; this probably results in a higher proportion of fines than if operated under non-choke conditions. Reduction in fines produced could be achieved by trickle feeding material into the jaw crusher; however this would have an adverse effect on particle shape and also it would reduce throughput capacity. Ideally, the feed rate should not be switched from choke to non-choke, as this would have a knock-on effect on the down-stream secondary processing plant. In practice, many jaw crushers are fed in this intermittent fashion due to gaps in the delivery of feed material from the quarry. Jaw crusher feed is pre-screened using a grizzly -screen prior to crushing; this is in order to remove material finer than the closed side setting.

Key finding

In practice, many jaw crushers are not fed to their design capacity; this is because the subsequent processing plant does not have sufficient capacity to handle the volume of material that would be produced if the jaw crusher were working to capacity.

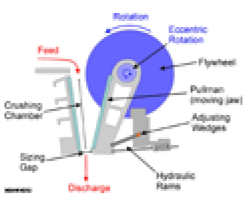

Figure 8. Jaw Crusher diagram

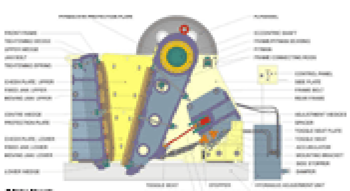
Figure 9. Detailed Jaw Crusher diagram

Crusher setting

Ideally, the reduction ratio of a jaw crusher should be 6:1; this is calculated as the ratio between the particle size of the feed (the F80 is used, this is the particle size at which 80% is finer than the top size of the feed) and the particle-size of the product (the P80 is used, which is the size at which 80% is finer than the top size of the crushed product). The finer the closed side setting (CSS) the greater the proportion of fines produced. The closed side setting of a jaw crusher is constrained by the need to maintain the nip angle within a narrow range (typically 19 to 23^{o}); too large an angle causes boiling in the crushing chamber (this is where the jaw plates cannot grip onto the rock and it keeps slipping up and down).

Key finding

Increasing the CSS in an attempt to reduce the amount of fines produced may have the opposite effect; it would lead to a greater proportion of oversize material, which would need *recrushing and would ultimately lead to a higher proportion of fines being produced.*

The settings on a jaw crusher are more designed for producing material for secondary crushing. The best particle shape is typically found in material that is approximately the same size as the closed side setting. Smaller sizes will contain a higher proportion of elongated particles because they have passed through the crusher without being touched. Larger sizes will also contain a higher proportion of elongated particles because long and narrow pieces have also passed through the crusher without being touched. This indicates that the closed side setting is best set to the size of the main product required to give the best results.


Photo 10. Primary Jaw Crusher

Cone and gyratory crusher good practice

Overview

Cone crushers (Figs. 11, 12 & 13) and gyratory crushers (Photo 15) consists of a cone that crushes material as it rotates within a crushing chamber. For further detail on how cone crushers and gyratory crushers work, click here. Cone crushers are used in tertiary roles as an alternative to impact crushers where shape is an important requirement but the proportion of fines produced needs to be minimised. Even though the reduction in fines produced may only be a few percentage points, this would represent a significant volume of material in a large operation.

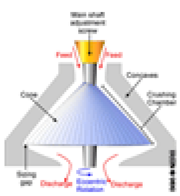
Figure 11. Cone Crusher diagram

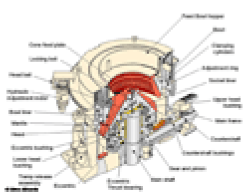
Figure 12. Detailed Cone Crusher diagram

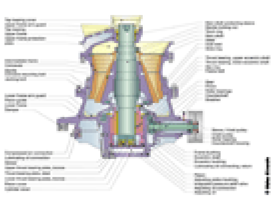
Figure 13. Secondary Cone Crusher diagram

Key finding
Cone crushers are mainly used in secondary and tertiary roles, therefore attempts to minimise fines production will have a greater effect on the overall production of fines compared to attempts at minimising fines production by primary gyratory or jaw crushers.

Feed

Uniform distribution of feed material around the cone crusher inlet is good practice as it allows production of a consistent product and consistent operation of the crusher. Choke feeding is important for cone crushers as it maintains a good particle shape by facilitating an inter-particle crushing action; trickle feeding is not a sensible option as it increases the proportion of flaky material in the crusher product.

Key finding
Pre-screening of the feed to remove the fines, especially in tertiary crushing is good practice; it helps to avoid packing of material in the chamber and maintain an effective crushing action.

It is advisable to maintain approximately 10-15% of material finer than the closed side setting in the feed to assist crushing action. Pre-screening to remove 6-10mm aggregate from the feed should be avoided as void space in the chamber results in an increased proportion of flaky material in the product.


Photo 15. Primary Gyratory Crusher

Crusher settings

The liner profiles are designed for a range of product sizes from extra coarse (EC) to extra fine (EF); the EF liner profile will result in the highest fines proportion for a given cone crusher.

Key finding
The finer the closed side setting the greater the proportion of fines produced.

Monitoring the crushing force, as registered through the load on the crusher motors and also the pressure on the hydraulic mantle adjustment mechanism, will give forewarning of crusher packing problems before they become too acute.

Impact crusher good practice

Overview

Impact crushers consist of a set of hammers that crush material as they spin within a crushing chamber (for further details click here). Impact crushers tend to be used where shape is a critical requirement and the feed material is not very abrasive. The crushing action of an impact crusher breaks a rock along natural cleavage planes giving rise to good product quality in terms of shape. The quality of these products makes them ideal for use in highly specified roadstone and concrete aggregate applications (Figs. 16, 17, 18, 19 & Photos 14 & 20).

Key finding
Improvement in product particle shape comes at the price of producing excessive fines.

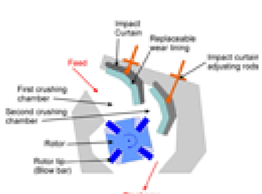

Figure 16. HSI Crusher diagram

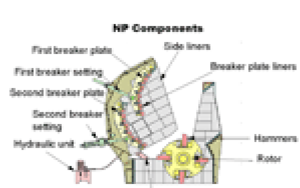

Figure 17. Detailed HSI Crusher diagram

Feed arrangement

It is vitally important that the feed arrangement to an impact crusher ensures an even distribution of feed material across the full width of the rotor. This will allow for even distribution of energy into the feed material and uniform wear patterns ensuring consistent product gradation and power consumption.

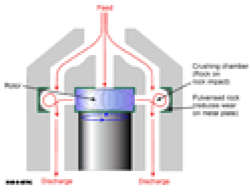

Figure 18. VSI Crusher diagram

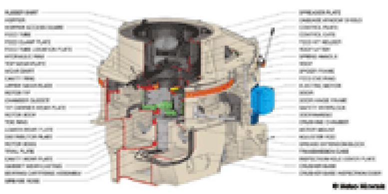
Figure 19. Detailed VSI Crusher diagram

Crusher settings

Size reduction in an impact crusher relies on energy being imparted into the rock from the rotor. This initial impact is responsible for more than 60% of the crushing action with the remainder being made up of impact against an adjustable breaker bar and a small amount of inter-particle collision.

Key finding
Size reduction is directly proportional to the rotor speed; it largely dictates the amount of fines produced. Slower rotor speeds can be used as a means of reducing the amount of fines produced but may result in a product with a less desirable particle shape.

Slower rotor speeds are preferable as a means of minimising the amount of wear on crusher components.


Photo 14. VSI at sand and gravel plant


Photo 20. Primary Impact Crusher

The product grading from an impact crusher will change throughout the life of the wearing parts particularly the impact hammers or blowbars. As the profile of the hammer changes with increasing wear, the product grading becomes coarser. Many modern impact crusher installations have a variable speed drive arrangement that allows an increase in the rotor speed to compensate for wear on the impact hammers.

Open discharge arrangements in impact crushers rely on retention of the rock within the crushing chamber. This is achieved by reducing the gap between the rotor hammers (crushing members) and the impact curtain.

Key finding

Decreasing the gap between the hammers and impact curtain increases particle retention in the chamber. This increases the size reduction ratio; however it also reduces throughput capacity and increases fines production.

Closed discharge arrangements rely on a series of grids to retain the material within the crushing chamber; these are generally not adjustable. Decreasing the size of the grid apertures has the effect of increasing the residence times of material in the crushing chamber. This increases the size reduction ratio; however it also reduces throughput capacity and increases fines production.

Washing plant

Overview

Washing plant performance has continued to improve over recent years, however there has been little incentive to treat water as anything other than a freely available and cheap commodity (Photos 21, 22 & 23). The need to comply with the legal and regulatory framework has always been the principal driver behind the protection of the natural water environment; recent changes in regulation will have far-reaching consequences for the quarrying industry. For further details on Quarry fines waste click here. For example, the recent implementation of time limited abstraction licences introduces the prospect that quarries may be forced to close due to failure to obtain a licence renewal. The risk to a business-as-usual approach should not be underestimated. Quarrying depends on long-term planning permissions and it is on this basis that large-scale capital investments are made. This is now out of step with the new abstraction licencing regime, under which abstraction licences could be terminated within a much shorter period, effectively bringing the life of a quarry to a premature end.

Key finding

There have been only limited signs of investment in more sophisticated approaches that promote the minimisation of water use and consumption.


Photo 21. Washing plant

Water is widely used in operations around a typical quarry site. Water use can have a number of detrimental effects, such as consumption (loss of water volume) and contamination, both of which ultimately may cause impacts on ground and surface water resources if not managed in an appropriate fashion. At other sites, water present on the site may not be used, but must still be removed in order to create conditions in which quarrying activities can proceed safely and efficiently. This may also create impacts on the water environment. The use of water efficient technology, water recycling and water reuse (for example, through the use of settling ponds or lagoons or other classification / filtration methods to remove contained solids) can all substantially reduce the overall consumption of water at a site.


Photo 22. Washer barrel


Photo 23. Washing plant cyclone

Washing plant good practice

Although water may be consumed on site in order to manage impacts associated with quarry fines (for example, to suppress dust), the most significant use at many sites is for the recovery of quarry fines from the aggregate in order to produce a clean product. Increasingly this is achieved in dedicated washing plants, which are designed to remove fine-grained particles and recover a clean aggregate product from crushed rock or sand and gravel.

Key finding
Washing plants represent the greatest opportunities for efficient water use.

Although a significant proportion of water used in a washing plant may be treated and recycled (either to the washing plant or for other uses around the site), there are still losses (such as moisture water in the product) that must be addressed through continuing inputs of additional water. In this respect, washing plant are water *consumers* as well as water *users*. While it is possible to reduce water *use* in the washing plant, it is important to balance such reductions with the associated loss in operational efficiency. It is important to focus on water *consumption* (that it, where water is lost and must be replaced). The most significant water losses occur outside of the washing plant during the treatment, discharge or recycling of the plant discharge. Ideally, water leaving the washing plant should be stripped of any suspended solids (and other contaminating materials as appropriate) and recycled back to the plant in order to limit unnecessary abstraction from surface water and groundwater resources. Options for cleaning the washing plant discharge include silt lagoons and thickener / filter press systems.

From a water use perspective, thickener or filter press systems may be preferable to silt lagoons, as water losses (via evaporation, ground infiltration) are largely avoided, reducing the top-up water that is required (Photos 24, 25 & 26).


Photo 24. Washing plant thickener


Photo 25. Filter cake from a plate press

Where water is in short supply, operators should take steps to properly store, manage and recycle all available water. This may require the proactive capture and routing of surface run off to on-site water holding areas. Water storage areas (and also silt lagoons) should be located on ground with low permeability in order to minimise water losses into groundwater. If practical (from technical, economic and environmental perspectives), it may be possible to consider the use of dry or water efficient processes to recover quarry fines. Dry recovery may not only minimise water use (thus reducing the environmental impact of mineral extraction) but also may remove the need for settling ponds and lagoons and enable easier handling of fines (potentially encouraging their use in other applications).

Key finding

It is important to note that at present, the feasibility of using waterless methods has only been established for a very narrow range of quarried materials.


Photo 26. Discharge into silt lagoon

Crushing Plant

Good operational practice for compression crushers, ensure that:

- the crusher is correctly specified, including capacity, stroke and crusher cavity;
- product volumes and gradings are monitored throughout the life of the crusher;
- feed material is the correct size for the feed opening, well-graded and free of fines;
- feed and volume are sufficient to maintain choke-feeding, even when feed is intermittent ;
- feed distribution is consistent to ensure an even loading on the crusher;
- crusher liners are correctly specified to ensure even wear and reduce packing;
- crusher setting is maintained to maximise product and balance total crusher loading.

Poor operational practice. Do not:

- trickle feed, as this may lead to product flakiness and high, uneven wear;
- reduce the amount of oversize material in the feed;
- feed undersize as this may lead to uneven wear and packing;
- assume constant throughput and product grading, as feed and crusher settings may vary.

Maintenance. Monitor:

- crusher-drive motor loads, high amps may indicate mechanical or crusher liner problems;
- crusher run down times, shorter times may give early warning of mechanical problems;
- cooling water temperature and oil pressure/ flow/ temperature;
- manganese spread; action may be required to avoid overstressing of machine frame or fouling of static members.

Technology: Extraction and Crushing

Extraction

Overburden removal

Overburden in hard rock quarries may include soil, sub-soil, unconsolidated younger rock formations, other contaminating rock bodies, and/or weathered materials. Unconsolidated overburden may be removed using excavators; wheeled loading shovels or hydraulic back-hoe excavators. Consolidated overburden may require blasting before it can be removed.

Overburden removal at sand and gravel operations has a greater emphasis on the reuse of overburden material as part of the ongoing restoration process. For further details on restoration click here. Overburden usually consists of soil, peat or glacial till; the thickness can range from less than 1 m to about 15 m. Overburden to mineral ratios are also highly variable and, although it is commonly quoted that they should not exceed 2:1, higher ratios are worked where the mineral is of good quality.

Wherever possible, overburden material is directly reused in site restoration; where this is not possible it is transported to a suitable site specified in the planning permission. Soils and sub-soils are carefully stripped using specially equipped hydraulic backhoe excavators and stored in special storage bunds. They require careful handling and storage if their physical structure and chemical characteristics are to be preserved. For this reason different layers within the soil are stored separately from each other so that they may be re-laid sequentially during restoration. Where possible soils will be directly placed onto previously worked out areas as part of progressive restoration.

Drilling and primary fragmentation

Drilling and blasting is carried out to fracture the rock to enable mechanical excavation. For further details on blasting, click here. It is normally essential in hard rock quarries; holes are drilled behind the working face and filled with an explosive (Photos 27, 28 & 29). When detonated, the rock is broken into manageable fragments to be taken away for further crushing and processing. Drilling and blasting is rare at sand and gravel operations; it is sometimes required prior to the excavation of more consolidated materials.

The most common blasting agent is ANFO, a mixture of ammonium nitrate (fertiliser) and fuel oil. Laser profiling may be used to characterise the quarry face before blasting so that the exact quantity of explosive is used (see Rock Blasting animation below). Blasting agents are often brought to site in separate form and mixed when inserted into the hole; often by specialist contractors. Use of blasting agents and explosives in quarries is regulated by the Quarries (Explosives) Regulations 1988. Poor blasting significantly increases production costs, it is therefore designed to obtain optimum fragmentation reducing the need for secondary breakage without producing excessive quarry fines (material finer than 4 mm).

 Photo 27. Before hard rock blast

 Photo 28. During hard rock blast

 Photo 29. After hard rock blast

Electronic detonators allow blasts to be triggered sequentially to minimise vibration. Careful design of the delay between blasts (the blast sequence) mean that the pressure waves from each blast interfere with each other and reduce vibration. The amount of explosive used in a blast is carefully measured to reduce the risk of fly rock (pieces of material that are thrown clear of the blast site).

There is a trade-off between blasting costs and crushing costs; if large rock pieces are produced by blasting the cost of crushing will be increased. Oversize rock slows the loading process and may exceed the maximum size set for the primary crusher, leading to reduced efficiency. It may also increase the maintenance costs for both loading and crushing equipment. Blasting generally tends to be optimised according to handling and crusher efficiency criteria. A recent project *Less Fines Production in Aggregate and Industrial Minerals Industry*[358] examined the potential for reducing the amount of fines resulting from blasting in quarries via the use of new blasting methodologies.

Through careful control of hole location, depth, detonation sequence and timing the blasting process can be optimised in terms of cost and minimising environmental and social impacts. The energy released when the explosive is detonated does not only go toward breaking the rock; some energy is lost via heat, sound (as noise), displacement and ground shaking (vibration). These are the main environmental and social impacts associated with blasting.

Key finding
Fragmentation on blasting is designed to produce material suitable for the primary crusher, but significant quarry fines may also be produced

In weaker, or inherently fractured, rock types, mechanical breaking (known as ripping) may be employed (Photos 30 & 31). A single tooth mounted at the rear of a powerful crawler-tractor is often used. Mechanical rippers enable the selective extraction of material and have less environmental impact than blasting. However, this is a slower process than blasting and may be uneconomical in high volume, large scale operations.


Photo 30. Bulldozer ripper in quarry


Photo 31. Bulldozer ripper close-up.

Further detailed information on drilling practices and options can be found at:

- www.pitandquarry.com/pitandquarry/article/articleDetail.jsp?id=17975;
- www.pitandquarry.com/pitandquarry/article/articleDetail.jsp?id=17976.

Further information on blasting is available at:

- www.pitandquarry.com/pitandquarry/article/articleDetail.jsp?id=17978;
- www.pitandquarry.com/pitandquarry/article/articleDetail.jsp?id=17979.

Secondary fragmentation

Depending on the primary fragmentation method used, it may be necessary to reduce the size of a proportion of rock on the quarry floor before it can be efficiently and safely handled by the excavators and trucks and fed to the crushers for processing. The most straightforward method is the use of a hydraulic breaker (also known as a hammer or pecker - Photo 32) or a drop ball (Photo 33). Secondary blasting by placement of explosive on or within the oversize rock can also be used. To remain cost effective a quarry operator will try to reduce the amount of secondary breaking required with a good blasting sequence.


Photo 32. Hydraulic breaker in quarry

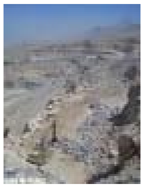
Photo 33. Drop ball in limestone quarry

Digging, loading and hauling

The methods employed for digging and loading are dependent on production rate, rock type and height of the pile of blasted material. Typically, either hydraulic backhoes (Photo 34) or hydraulic face shovel excavators (Photo 35) (which have a high bucket filling efficiency and can hold up to $10m^3$ in a single load) are used.

Hauling of the blasted rock to the processing plant is most often carried out using rigid dump trucks, with capacity ranging from 15 to 100 tonnes. Hauling is a major cost in quarrying operations and much attention is given to gradients and surfaces of access ramps and the distances travelled. A system of fixed conveyors, which can operate on a much steeper gradient than dump trucks, is sometimes a cost-effective alternative (Photos 36 & 37). In many operations a mobile primary crusher is used, allowing the machine to be brought up to the face, where it can be fed directly by the excavator.


Photo 34. Loading with backhoe


Photo 35. Loading with face shovel


Photo 36. Sand and gravel conveyor


Photo 37. Crushed rock conveyor

Sand and gravel

Sand and gravel is either worked in wet or dry conditions. Wet quarries may be dewatered, where pumps are installed after the initial excavation to draw down the water table, and worked dry (Photo 38). Dry working is the most efficient in terms of maximising extraction and it also enables more selective extraction. Where deposits exceed 5 m, dragline excavators are extensively employed; these are robust and efficient at feeding conveyor systems. Where deposits are thinner or more consolidated, hydraulic backhoes are used. Some very unconsolidated deposits, such as dune sands or some glacial deposits may be excavated directly from the face by wheeled front-end loaders. Wherever possible, conveyors are used for haulage in preference to dump trucks; field conveyors can be several kilometres long, and transport up to 1000 tonnes per hour.

 Photo 38. Sand and gravel extraction

In wet quarries, at depths of less than 10 m, long-boom draglines can be used, the main disadvantage of these being a high loss of fine sand (Photo 39). In deeper water, grab dredgers are used. Difficulty in maximising extraction in wet quarries comes from being unable to visually inspect progress in the working and identify those areas from which more extraction is possible. Given that initial capital investment in dredgers is high and the quarrying process is less efficient most operators prefer to work sites dry and will employ pumps to temporarily lower the water table when workings would otherwise be flooded.

 Photo 39. Sand and gravel dredging

In general, due to the small particle size of extracted material, it is easier to use conveyors to move material from the extraction area to the processing plant at sand and gravel operations than at hard rock quarries. However, hauling via trucks is still commonly used, with the choice of conveyor or truck being made based on economics and environmental / social considerations.

Marine-based sand and gravel is worked by trail dredging (Photo 40), where a suction pipe is pulled across the sea bed at slow speed (between 1 and 3 knots). The passage of the pipe across the sea bed leaves a groove about 2.5 m wide and 0.25 m deep and allows relatively thin deposits to be worked, whilst the substrata below the deposit remain largely undisturbed. Deposits at water depths of up to 40 m can be worked. The largest dredgers can load at a rate of 2000 tonnes per hour. Water and solids are pumped into the hold, with water displaced by additional dredged material as dredging proceeds. Primary screening takes place on board the dredger but the main processing takes place at a land-based processing plant. Marine deposits are usually of high quality (with a low percentage of fines) and can be landed directly into areas of high demand. Various techniques for unloading are used, but increasingly ships are self unloading, using pumps to unload. The high capital cost of these specialised dredgers drives the need for minimising the time spent away from the dredging sites.

 Photo 40. Marine dredging

---

Crushing plant technology

Crushing, a type of comminution, is carried out to produce particles of a given size distribution and particle shape. The most common types used are compression crushers and impact crushers . Many crushers also incorporate a component of abrasion and attrition which leads to the production of fine material. The physical and mechanical properties of a rock govern the way it breaks apart. Brittle minerals with inelastic behaviour will fracture when subjected to sufficient stress; the presence of cracks or flaws in the crystalline matrix of the mineral will act to concentrate stress, resulting in crack propagation and ultimately fracturing. Some minerals display elastic behaviour, whereby stress is absorbed by distortion of the crystal matrix without fracturing. Fracturing preferentially occurs along cleavage planes, grain boundaries, laminations, bedding planes, foliation, joints and other planes of weakness. Compressive crushing produces material that consists of two distinct size ranges; coarse particles formed by tensile fracturing and fine particles formed by compressive fracturing. Impact crushing produces material with a uniform particle shape and size. Crushing is usually performed dry and in several stages .

The energy used by crushing equipment causes distortion and fracturing, which creates new surfaces. The amount of energy used to create these new surfaces is approximately 2% of that used in the crushing process; the remainder is lost as sound, heat and vibration. Crushing of brittle material uses less energy than crushing of elastic material; the latter may change shape rather than fracture. Comminution theories used to determine the amount of energy required for crushing often assume brittle behaviour.

Crushers applying a steady continuous compressive stress, such as roll crushers, which are not ideally suited to the minerals industry, consume the lowest energy per unit volume. Jaw, gyratory and cone crushers consume the most energy, and impact crushers are intermediate consumers. The Bond Work Index is the commonest measurement of grindability; typical values are shown in Table 3. The selection of a crusher is made by considering the type of material to be crushed, the feed size, throughput, the required product size and quality, the product's commercial value, as well as the capital cost, power requirements, operational costs and environmental restrictions relating to the crusher. There is a direct correlation between the Bond Work Index and the capital investment required; the harder the rock the more crushing stages and/ or larger equipment is required. A crusher that is ideally suited technically may not be the best choice when economic factors are brought into play. Also, the performance of a crusher will be reliant upon the crushing plant which it is part of; therefore it is important that decisions regarding new equipment are made after crushing trials using the largest practical volumes of the material to be worked. [359]

Production + Process Technology			Table 3
Bond Work Index (Wi, kWh per tonne)			
Mineral	Work Index (Wi)	Mineral	Work Index (Wi)
Barite	4.7 - 6.9	Glass	3.4
Basalt	17.0 - 22.5	Granite	15.1 - 16
Cement clinker	14.8	Limestone	9.0 - 12.8
Coal	12.5 - 13.0	Mica	148.0
Dolomite	9.0 - 12.4	Quartz	13.6 - 14.1
Feldspar	12.8	Quartzite	9.6

NB Values were taken from two sources [377, 378]; some quarries have values that vary significantly from these.

Crusher throughput capacity is typically quoted in tonnes per hour (tph). The nature of crushing is essentially volumetric and capacity figures typically refer to rocks with a bulk density of 1600 kilograms per cubic metre (kg/m^3). The product yield is more important than the throughput capacity; 100 tph of crushed material with 30% oversize only results in 70 tph of product, whereas a crusher that produces 85 tph of crushed material with 5% oversize results in 80 tph of product.

Jaw crusher

A jaw crusher consists of two plates inclined toward each other; the "swing" jaw plate is pivoted such that it moves relative to the other fixed jaw plate (Figs. 8 & 9). The angle between the plates (the nip angle) is typically 19^o to 22^o. The swing jaw is powered by a flywheel and is braced with a toggle plate; this controls the crusher product outlet and is a release mechanism for uncrushable material such as tramp iron. Crushers with a single-toggle plate design have a more direct connection to the flywheel which imparts a circular elliptical movement to the swing jaw; whereas crushers with a double toggle plate design are connected to the flywheel via the toggle plates which imparts a back and forth motion to the swing jaw.

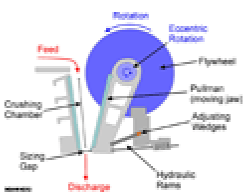

Figure 8. Jaw Crusher diagram

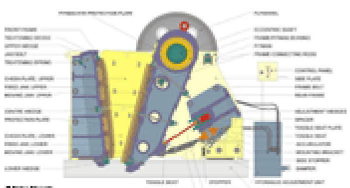
Figure 9. Detailed Jaw Crusher diagram

In most jaw crushers, the flywheel has substantial mass; this helps to maintain rotational inertia and evens out power requirements. The circular-elliptical movement of the swing jaw helps to pull feed material through the crushing chamber. The jaw plates have manganese steel liners, with a corrugated or other surface profile designed to optimise crushing; these liners can be reversed to ensure even wear or replaced when worn out. Wear tends to be focused at the bottom, where the gap between the jaw plates is the smallest. The product outlet size is defined by its closed side setting (CCS) and open side setting (OSS). The amount of movement between the plates (crusher throw) varies between 1 and 7 cm. A short throw is used for fine-grained, brittle, hard rock and a longer throw for more coarse-grained, tough, elastic materials. Incorrect selection of the throw can lead to overheating of bearings, increased power consumption and reduced throughput. 350

Material is fed into the jaw crusher via a hopper; the opening width ranges from 0.8 to 2 m and the gape (gap between the crusher plates) from 0.25 to 1.2 m (Photo 10). Feed may be pre-screened to prevent undersize from entering the crushing chamber. This increases the capacity of the crusher, reduces the risk of product contamination and choking in the crusher.


Photo 10. Primary Jaw Crusher

Key finding
The jaws are kept full (choke fed) to reduce jaw impact, reduce the amount of slabby material

and minimise wear, especially where abrasive material is being crushed.

As feed material works its way down through the crushing chamber it is nipped and released several times as the plates move in and out (Jaw Crusher animation below). The nip angle is kept within a close range to ensure that material does not slip and that maximum size reduction is achieved. The number of crushing actions is controlled by the rotational speed of the flywheel, the profile of the jaw plate liners and the feeding conditions. The particle-size of the product varies due to the state of wear on the crusher liners and toggle plates; the CSS is monitored to avoid the product drifting out of its required size range. Reduction ratio are typically in the range 7:1 to 8:1; this varies with ratios up to 10:1 for limestone and as low as 5:1 for hard rocks such as granite.

Smaller jaw crushers have 100 kW or smaller motors and flywheel speeds up to 300 rpm, larger crushers have motors greater than 250 kW and flywheel speeds as low as 200 rpm. Each turn of the flywheel is equivalent to a complete crushing action i.e. full opening and closing of the swing jaw. Double-toggle crushers have an intermittent cycle, with crushing only taking place in the chamber during the forward stroke of the swing jaw. Single-toggle crushers have a continuous crushing cycle; when the upper feed inlet is opening the lower product outlet is closing; therefore crushing is always taking place at some point within the crusher.

The production capacity of a jaw crusher is directly proportional to the CSS; increasing the CSS allows more material to be discharged through the outlet. A crusher with a feed opening of 1000 mm will produce 125 tph at a CSS of 70mm, whereas at a CSS of 200 mm it will produce four times as much. Increasing the CSS also decreases the amount of comminution that takes place; a 70 mm CSS will result in a product with approximately 40% finer than 40 mm, whereas when using a 200 mm CSS this is only 15%. Crushers with a larger gape and wider crusher plates have a higher production capacity for a given CSS, for example at a CSS of 175 mm a jaw crusher with a feed opening of 1000 mm will produce 300 tph, whereas a jaw crusher with a 2000 mm feed opening will produce up to three times as much.

Cone crusher

A cone crushers consists of an inverted cone (the bowl or concave) that sits over a conical head (Figures 11, 12 & 13). The feed inlet is at the apex of the crusher; the crushing chamber (or cavity) tapers from the feed inlet to the product discharge outlet. The crushing surfaces are protected with high manganese steel liners; the head liner is known as the mantle. The head is seated on a vertical shaft that is driven by spiral bevel gears connected to a counter shaft. This causes the head to move in an elliptical path around the main shaft;

viewed in cross-section the crushing action is similar to that of a jaw crusher. Unlike a jaw crusher, the rotational speed of the motor does not directly equate to the number of crushing actions; this is due to the gearing between the counter shaft and main shaft. A flywheel (sheave) is attached to the countershaft to maintain inertia. Hydraulic mechanisms control the crusher CSS; they also act as an emergency release mechanism for removal of uncrushable material such as tramp iron. The amount of movement between the head and the bowl is known as the eccentric throw (difference between the CSS and OSS); increasing the throw will increase throughput capacity but may have an adverse effect on product particle shape.

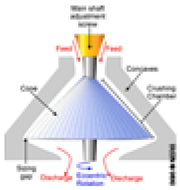
Figure 11. Cone Crusher diagram

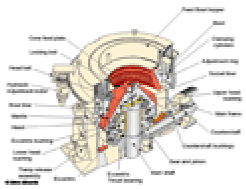
Figure 12. Detailed Cone Crusher diagram

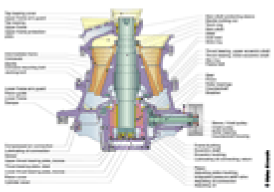
Figure 13. Secondary Cone Crusher diagram

It is recommended that material be fed into the crusher using a distributor to maintain an even distribution of well-graded material throughout the crushing chamber. The particle size of the feed should be controlled so that it readily enters the chamber and fine material is removed. Increasing the moisture content of the feed material can be used to avoid packing of material in the cavity; water flush can be used to increase the throughput capacity.

Key finding
Cone crushers rely on a full chamber (choke feed) to give the best results. Failure to choke feed results in lower quarry fines production, but also reduced capacity, poor product shape and uneven crusher liner wear.

Feed material works its way through the cavity and is discharged through the outlet (Cone Crusher animation below). The gap between the head and concave becomes narrower toward the bottom; whereas the diameter of the cavity becomes wider. The cone crusher delivers a straightforward horizontal impact; material is nipped and released approximately six times in the cavity. The cavity can be divided into annular crushing zones; the volume of these zones increases towards a choke point. The point of optimal crushing is typically at the base of the chamber. The reduction ratio is typically 6:1 to 8:1 for secondary crushing and 2:1 to 3:1 for tertiary crushing. Cone crushers operate a continuous cycle; crushing takes place in the chamber 100% of the time.

Key finding

Increasing the rotational speed of the crusher can increase the throughput capacity; but it may increase the residence time in the cavity which will have the effect of reducing throughput capacity and increasing fines production.

The production capacity of a cone crusher is directly proportional to the CSS; increasing the CSS allows more material to be discharged. The size of the cavity is controlled by the use of different liners; cavity size ranges from extra fine (EF), fine (F), medium-fine (MF), medium (M), medium coarse (MC) coarse (C) and extra coarse (EC). As a rule, finer cavities result in finer products. There are two types of head used; the standard head and short head. Short head cone crushers are used for finer crushing. Some heads have a stepped profile that allows finer crushing, albeit at a lower throughput capacity. The profile of the liners can be monitored to ensure that efficient crushing is taking place; regular analysis of the crusher product will help to indicate when liners need to be replaced.

Cone crusher throughput capacity decreases with decreasing CSS. A cone crusher with an Extra Coarse cavity (feed opening, 299 mm; CSS, 25 mm) will produce up to 380 tph whereas the same cone crusher with a Fine cavity (feed opening, 107 mm; CSS, 13 mm) will produce up to 185 tph;. However, less comminution takes place; a 13 mm CSS will result in a crusher product with 66% finer than 10 mm, whereas this is only 30% with a 25 mm CSS. Larger crushers have a higher production capacity for a given CSS due to the increased volumetric capacity within the crushing chamber.

Gyratory crusher

Gyratory crushers are similar to cone crushers; they are frequently used in large-throughput primary crushing roles (Photo 15 & Fig. 41). Typically, they have larger capacities (up to 8000 tph) compared to jaw crushers (up to 1500 tph). Gyratories operate at a slower speed than cone crushers, typically in the range 85 to 105 rpm. They do not require feed mechanisms and are usually fed direct from the back of a dump truck. The available feed opening area of a gyratory crusher is approximately three times greater than that of a jaw crusher of a similar gape; the gyratory has a higher capacity.


Photo 15. Primary Gyratory Crusher

The most commonly-used type is a supported-shaft gyratory crusher; the main shaft is suspended from an overhead spider. The angle of the mantle is steeper than that used in a cone crusher; because of this gyratory crushers have a smaller throw. This affects the flow of material and improves the particle shape as material is struck more frequently in the crusher cavity. The CSS is adjusted by raising or lowering the head.

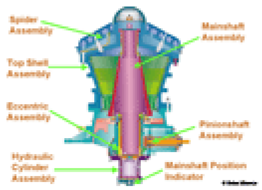

Figure 41. Detailed Gyratory Crusher diagram

It is desirable for gyratory crushers to be run under choke feeding conditions; however this may not always be the case in practice as there are usually gaps between deliveries of feed material by dump truck. The particle-size of the product may vary over time due to the state of wear on the crusher liners and concaves; the CSS of the crusher is monitored to avoid the crusher product drifting out of its required size range.

Where gyratory crushers are used in secondary, tertiary and subsequent crushing roles they have similar operating principles to primary gyratory crushers. They tend to be more tolerant of variations in feed material and feed rate than cone crushers.

Roll crushers

Roll crushers have limited application in the quarrying industry, aside from their use in limestone operations; this is largely because of their low throughput. They tend to be used for sedimentary, friable rock and wet or sticky materials that jaw or gyratory crushers struggle to process. These crushers use a combination of impact, shear and compression to break up the feed material; they can be subdivided into sledging or slugger rolls, and crushing rolls.

Sledging or slugger rolls have either a single or double-roll construction. A single-roll sledging crusher consists of a heavy roll with rows of teeth (or picks) that are used to grip the rock and feed it into the crushing chamber. Facing the roll is a breaker plate; the distance between this plate and the roll is the crusher setting. A two-roll slugger crusher consists of two toothed rolls. A mineral sizer is similar to a two-roll slugger but with more pronounced teeth that are staggered on the contra-rotating rolls; this helps to increase the capacity by allowing the passage of undersize material and enabling a relatively high reduction ratio. Crushing rolls consist of double, contra-rotating rolls that act primarily as compressive crushers; they are especially used for friable, non-abrasive material.

Impact crusher

In the past, impact crushers were mainly used for crushing non-abrasive materials, such as limestone. The development of abrasion resistant wear-parts has increased their use for the crushing of abrasive rocks, such as sandstone.

An impact crusher consists of a crushing chamber lined with impact plates or bars (known as anvils or breaker plate); within this chamber is a rotating shaft with fixed rotors that support metal bars (known as beaters, impellors, hammers or blow bars). The shaft may be horizontal (Horizontal Shaft Impact crusher (HSI); Figs. 16, 17 & Photo 20) or vertical (Vertical Shaft Impact crusher (VSI); Figs. 18, 19 & Photo 14). HSI crushers are generally used for coarse (primary and secondary) crushing; VSI crushers are used mainly for finer (secondary and tertiary) crushing. Some HSI crushers have double-rotors; the first for coarser material and the second for finer material. VSI crushers are either rock-on-metal or rock-on-rock; the latter type has lower wear on crusher components.

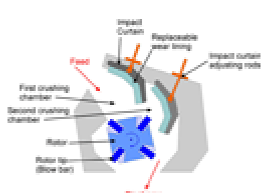

Figure 16. HSI Crusher diagram

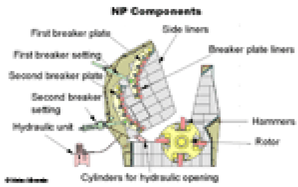

Figure 17. Detailed HSI Crusher diagram

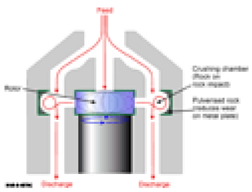

Figure 18. VSI Crusher diagram

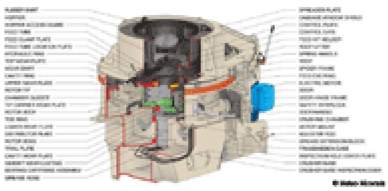
Figure 19. Detailed VSI Crusher diagram

A hammer mill is a form of HSI crusher with pivoted hammers that are allowed to swing freely (swing-hammer) within the crushing chamber. They are typically used in secondary or tertiary roles and are commonly used in limestone operations.

The impact crusher shaft rotates at a speed that is inversely related to its rotor size. In VSI crushers, the smallest rotors are 0.3m in diameter with shaft rotations up to 5300 rpm; the largest rotors are 1.2m in diameter with shaft rotations as low as 800rpm. In HSI crushers, the smallest rotors are 0.4m in diameter and 0.6m wide with shaft rotations up to 1500 rpm; the largest rotors are 2m in diameter and 2.3m wide with shaft rotations as low as 280 rpm. The relative velocity at the end of the rotor (tip speed) is within the range 35 to 90m/s. Speeds of 30 to 40 m/s are used to produce all-in material and 60m/s for manufactured sand. HSI crushers tend not to be operated above 60 m/s. VSI crushers that utilise rock-on-rock crushing operate at 55 to 70 m/s. Swing hammer mills operate up to 90 m/s.


Photo 14. VSI at sand and gravel plant


Photo 20. Primary Impact Crusher

Feed material is broken by direct contact with the beaters, metal surfaces or feed material. It is fed tangentially into the path of the beaters, which deliver a series of sharp blows to the particles and accelerates them into the crushing chamber. The first contact causes the largest degree of comminution; fractured material then passes from one breaker plate to another, travelling along a grinding path. The crushing chamber is usually lined with feed material; this minimises wear on the crusher parts. VSI crushers incorporate a dual feeding system that separates the feed into two streams; one fed to the rotor (rotor feed), whereas the other is fed directly into the crushing chamber (crushing chamber feed). Different manufacturers refer to this as a hydracascade or bi-flow feed system. This increases the rock-on-rock interaction (semi-autogenous crushing) and reduces the wear on crusher parts. Unlike crushing by compression, impact crushed material tends to have no residual stress, which is important for material used in construction. Also, it is useful for crushing more plastic material.

Key finding

In VSI crushers, decreasing the ratio of rotor feed to chamber feed will increase the particle-size of the product; reduce the fines content and the product size-distribution is narrower.

HSI crushers have a maximum feed size that ranges from 250 to 1900 mm and capacities ranging from 40 to over 1000 tph. VSI crushers have a feed size that ranges from 20 to 76 mm and capacities that range from 3 to over 2000 tph. Optimising the rotor speed, breaker plates, crushing chamber feed and rotor diameters, can be used to control the reduction ratio and product grading.

Key finding

VSI crushers are used as a shaping machine to produce a good cubical shape with a low flakiness however many fines may also be produced.

The proportion of flaky material in aggregate can be reduced by up to 50% by using a VSI crusher. It can also be used to remove undesirable material such as thinly intercalated shale, which is pulverised, leaving the harder sandstone as a coarser aggregate.

Technology: Washing Plant

Washing, classifying (separation by size or weight) and dewatering of processed aggregate are important activities at most sand and gravel quarries and at an increasing number of hard rock quarries (Photo 21). These activities are carried out in a washing plant, which takes the quarried material, uses wash water to remove silt and clay, and recovers clean aggregate products (sand and gravel, and crushed rock aggregate). The material removed consists of silt- and clay-sized material (finer than 63 microns) that is naturally present in sand and gravel, or is created during extraction (e.g. blasting) or during subsequent processing (e.g. crushing). Silt and clay may be present as a coating on grains of sand and larger rock fragments or present as discrete particles. Washing improves the efficiency of other activities such as crushing and screening and the quality of the final product. It may also be used to recover fine sand as a commercial product or as material to be blended to create another product.


Photo 21. Washing plant

A typical washing plant will aim to remove 96 - 98% of material below 63 microns and 100% of material below 150 microns. Removal of the silt and clay from the wash water is required before it can be re-used or discharged to the local water environment. Re-use is increasingly important as control of water abstraction becomes more stringent.

Typically, washing plants consist of a selection of equipment drawn from the following list, used in series or parallel as appropriate to a particular operation's requirements:

- Scrubber barrels: clean stone, gravel and sand by attrition ;
- Log washers: remove tough or plastic clays from sand and gravel and crushed materials;
- Sand screws: separate water and silt from sand;
- Gravel washers: wash coarse sand or crushed stone and gravel and dewater the cleaned material;
- Hydrocyclone classifiers: reclaim fine sand, using centrifugal force to separate coarser material from fines;
- Classifying tanks: recover coarser material (sand) from large volumes of water through settling;
- Thickeners, plate filter presses and belt filter presses: recovery of clean water (for re-use or discharge) by removal of clay and silt (as a filter cake with a low moisture content) (Photos 24 & 25).

 Photo 25. Filter cake from plate press

Other common equipment includes dry and wet screens, which are described elsewhere. For further details on dry process screening click here. Not all the items noted above are always necessary. A typical washing plant flowsheet might include:

- feed hopper and conveyor (with a magnet to remove tramp metal);
- gravel washer (e.g. for separation of coarse and fine aggregate);
- sand screw;
- hydrocyclone to remove minus 63 micron material;
- dewatering screens;
- thickener and filter press or a silt lagoon (Photos 42);

 Photo 42. Silt lagoon

 Photo 43. Sand tower and stockpile

Although not strictly defined as part of the washing plant silt lagoons (also known as settling lagoons) are an integral element of managing dirty water produced by the plant (and recovering clean water for recirculation back to the plant at some operations) and they are therefore also considered here.

A washing plant can be small relative to its throughput. Compact washing plants are becoming more common and can be installed in the floor of the quarry, at quayside operations producing aggregate from marine sand and gravel and in urban locations where secondary aggregates are being produced. By choosing the appropriate type and number of unit processes, washing plant can be designed for small, medium and large-scale applications. Generally, as the throughput increases, so does water ***use***. It is important, however, to distinguish between water *use* and water *consumption* see Figure 1).

Water passing through the washing plant may be recycled back to the plant, reused elsewhere on the site or discharged. Each of these options will require treatment of the contaminated wash water to remove contaminating silt and clay (the degree of treatment may be different depending on the chosen option; acceptable standards for reuse of water on-site may be lower than for discharge to local surface waters). Although there are significant opportunities for recycling of water, top up water is still required in all washing plants. Therefore, washing plant are water *consumers* as well as water *users* .

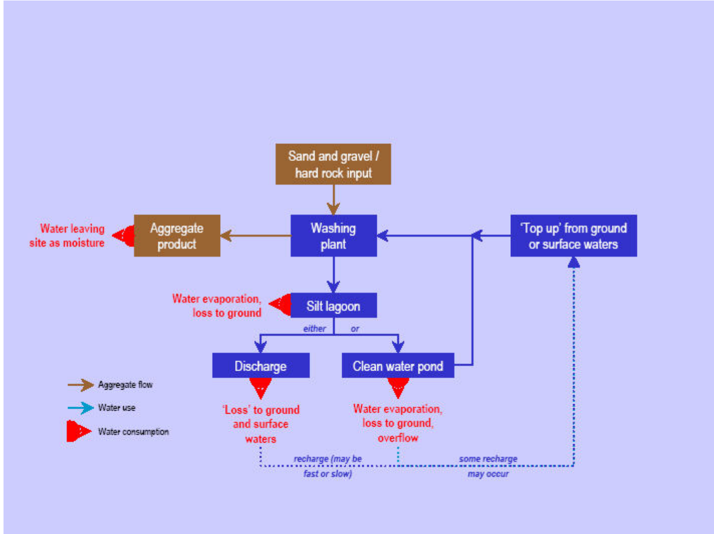

Figure 1. Water use and water consumption. *Copyright BGS NERC.*

Until recently there has been little incentive to treat water as anything other than a freely available and cheap commodity and only limited signs of investment in approaches that promote the minimisation of water use and consumption. A rapidly evolving regulatory framework means that this approach must now change. Growing pressure on water use by quarrying operations will encourage water-saving and may encourage (and make economically viable) the application of dry processes (for further details click here) to remove quarry fines as an alternative to the washing plant. In some UK locations an excessive use of water by industry is putting water-based ecosystems at risk and ongoing climate change is likely to have a significant negative impact on water availability.

Scrubber barrels

Scrubber barrels are horizontal drums (occasionally with a slight slope) in which feed material is cascaded with water, using attrition and impact to remove silt and clay present as discrete particles or as coatings (Photo 22) . Generally, the feed material and process water are introduced together at the lower end of the drum, which rotates and agitates the feed/ water mixture. Lifters (otherwise known as baffles) can be fitted within the scrubber to facilitate cascading and to help move the feed along the scrubber. The wash water flows over a weir at the upper end onto a screen, which separates the silt and clay from the sand and gravel.


Photo 22. Washer barrel

Scrubber barrels are generally autogenous that is they rely on the tumbling action of the material and interaction between the particles to remove the silt and clay. Residence time is relatively short, of the order of two minutes or so. The configuration (diameter to length ratio) can be chosen according to the degree of washing/cascading action that is required for optimum liberation of fines. Throughput is determined by the size of unit, ranging from less than 100 up to 500 tonnes per hour. Larger throughputs can be delivered through the use of appropriate units in parallel. The barrels require 23 to 68 litres of wash water per minute depending on the feed rate[351].

Key finding

A 500 tph scrubber barrel, 4 m in diameter, might use up to 800 m^3 of water per hour, but the *vast majority of such water can be captured, cleaned and recycled, reducing consumption to a smaller top up amount.*

Scrubbers are generally used to begin the process of removing silt and clay from the raw feed, but they may not fully liberate the silt and clay from the feed material. Where scrubber barrels do not offer a suitable level of performance, log washers can be used (e.g. for the treatment of difficult contaminating clays that cannot otherwise be effectively removed).

Log washers

Log washers are comprised of a gently sloping trough (5 - 10º, with 8º being typical) full of water, within which shaft-driven paddles rotate (the shafts were originally made from logs and this is where the name originates). Feed is fed in at the lower end of the unit, while water is fed in at the upper end. The abrasion-resistant paddles transport the feed upwards against the flow of water. The rotating paddles maximise attrition and allow the washers to remove clay, agglomerated rock, soft stone, friable waste and fine sand from the feed material. Clay, fine sand and other materials are removed via an overflowing weir at the lower end of the washer, while cleaned aggregate is discharged at the upper end (often onto a rinsing screen).

Light duty washers are used to handle materials that require only moderate scrubbing. Heavy-duty washers (with a higher-rated motor, thicker shafts and heavier paddles) are used where plastic clays are present that resist moderate scrubbing.

Increasing the trough slope reduces the throughput and increases the retention time, increasing exposure to abrasion and cleaning action on the feed material. Conversely, lowering the slope increases the capacity, but reduces the abrading action and retention time. The log rotation speed can also be adjusted upwards to increase the scrubbing effect. However, this can be counter-productive if it substantially reduces the residence time.

Generally, log washers are most efficient when dealing with narrow feed size ranges (e.g. 40-20 mm or 20 mm [351]), taking feed up to 40 mm in diameter, and therefore some pre-screening may be necessary to improve efficiency.

Sand screws

Sand screws (also known as fine material washers) are based on the principle of the Archimedes screw with a drain trough to one side. As the washed material is conveyed up an inclined box via a spiral screw shaft, water drains back into the dewatering trough. From there the water drains back into the settling area and is discharged via an overflow weir. The ideal operating angle for a sand screw is 18º from the horizontal. The pitch of the screw is designed to convey the maximum amount of material at this operating angle. Sand screws can be of substantial size (e.g. 2 m diameter, 10 m length) and handle several hundred tonnes of material per hour. An alternative to a sand screw is a bucket wheel classifier, which performs the same function but operates by scooping the sand out of the classifying tank (Photo 44).

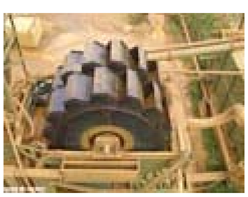
Photo 44. Classifying tank

The sand screw performs three functions: removal of water (dewatering), classification and washing. They remove excess water from washed sand so that the sand can be conveyed and stockpiled. By adjusting flow (velocity) and depth of water in the settling pool, they can be used to effectively classify material and generate a range of products. Although these sand screws are generally most effective in generating fine sand in the size range 63 to 150 microns, by adjusting the setting rate, products with coarser or finer size gradings can be generated. The action of flowing water carries away silt, clays and other lightweight materials (such as wood and organic matter) generating a washed sand product. The tumbling of the sand also produces an abrading action of sand against sand, which helps to remove coatings of clay and other materials as the screw moves the sand up the slope.

When choosing the size of a sand screw, the type of material, its size analysis, the desired product specification, the required production rate and availability of water are all important factors. It is better to choose one that is too large (over-sized) as it is possible to slow the screw speed to deliver the required performance, while it is not possible to increase screw speed on an under-sized unit without detrimentally affecting performance (e.g. by loss of material into the overflow).

The position in the washing plant will vary according to particular application, but will in general be in the final stages (as the output is generally considered to be a product). Sand discharged from a sand screw is dry enough to be transported directly to storage.

Sand screws are very efficient in the removal of fines and the production of a fine sand product. They are particularly useful where some additional (secondary) scrubbing is required to remove coatings present on the desired material fraction. However, the density of slurry in the settling pool must be carefully controlled; an increase in density can result in more coarse particles being lost with the overflow discharge. Equally, an increase in screw rotation can cause agitation in the settling pool and the subsequent loss of particles above the lower cut-off size. Water discharged from sand screws may require treatment (for example in a silt lagoon or thickener / filtration unit) to remove the contained fine material prior to offsite discharge or reuse within the washing plant or elsewhere onsite.

Unlike classifying tanks, sand screws cannot produce more than one product (with a defined particle size range) at a time nor can they remove excess materials from the middle of the gradation range (being limited to the removal of excess fine or coarse material). If these applications are required, then a classifying tank may be more appropriate.

Gravel washers

Also known as coarse material washers, gravel washers scrub, rinse and dewater coarse sand, crushed stone and gravel. A shaft with a combination of paddles and spiral segments conveys the material through the washer. The paddles serve two functions scrubbing and fluidisation. By agitating the bed of material the rock-against-rock interaction helps scrub clay and coatings from the gravel. Fluidisation facilitates the removal of unwanted lightweight material from the gravel by allowing it to float free and be removed via an overflow. The spiral segments are primarily used to convey material through the unit and increase the handling capacity of the unit (paddles alone are relatively ineffective at moving material through the washer). The spirals also help wash the gravel by rolling the bed of material.

Gravel washers can be used for several applications. They can be used simply for washing or the removal of unwanted materials. They can also be used for scrubbing the raw feed prior to screening. The configuration of the unit will depend on the nature of the application. They are particularly effective for the removal of organic matter, soil, dispersed clays, and other unwanted lightweight materials in the size range 3 - 75 mm.

Hydrocyclone classifiers

These fine sand reclaiming units have no moving parts (Photo 23). They operate on the principle of centrifugal force, which separates coarser size fractions from finer size fractions. They are often used for the separation of silt and clay from sand, as well as the production of concrete and building sand products. For the removal of silt and clay they normally operate with a cut point in the 40 - 75 micron range; for the production of sand they operate with cut points in the 100 - 250 micron range. The cut point can be adjusted, for example, by changing the internal diameter of the outlets or by adjusting the flow/ pressure of the inlet.


Photo 23. Washing plant cyclone

Key finding

Using a hydrocyclone gives an accurate cut point because it works on a combination of particle density and particle size. The result is less waste silt and a better quality sand product at the lower end of the particle size range.

Feed is pumped into the hydrocyclone through a tangential entry, which imparts a swirling motion to the feed suspension. This generates a vortex (central air core) within the hydrocyclone. Coarser (and denser) particles move outwards to the inner wall of the unit and then move down through the apex valve discharging as an underflow product. The finer particles, and most of the water, are discharged through the vortex finder into the overflow product. Any water leaving in the underflow product will carry with it fine solids. Therefore to produce a clean sand product it is common practice to use a second stage hydrocyclone to treat the diluted underflow product from the first stage.

Classifying tanks

Classifying tanks are rectangular in shape, 23 m wide, and up to 10 m in length. They are used to recover sand from large volumes of water by the process of settling. Through the use of multiple discharge valves at the base of the tank, they are able to generate more than one sand product (based on particle size). These products are generated as thickened slurry that requires further processing, such as dewatering, before it is ready for stockpiling and sale. The tanks also efficiently recover water. These tanks may be used prior to the sand screw in order to reduce excess water (and thereby reduce the size of the washer).

A sand/water slurry of pre-screened material less than approximately 10 mm enters the classifying tank through a feed box, which is designed to slow the velocity and direct the flow of slurry as it enters. The slurry stream progresses along the tank, with the particles settling in a position determined by their density and mass. This means that the coarsest particles settle nearer to the feed box, and finer materials settle progressively further down the tank, separating the sand into its component sizes. Silt and other lightweight unwanted material overflow the weir with the process water.

A range of particle sizes will accumulate at any given point along the bottom of the classifying tank. The narrowness of the size range is determined by the length of the tank, the flow of water, and, less importantly, the overflow head of the wastewater.

Discharge valves are placed along the bottom of the tank (normally 6 to 11, depending on the length of the tank). Material released from these valves is continuously recombined in appropriate proportions of fine and coarse particles to produce the desired end product. The blended product then proceeds to further dewatering. A control system is used to ensure that the blending process is conducted both accurately and efficiently by diverting varying portions of the sand accumulating at each valve station to each of the sand products (according to a predefined recipe for that specific product). A properly controlled classifying tank is able to simultaneously produce two controlled (blended) products and one residual product. The general strategy is to generate a primary blended product that uses most of the sand available to it, a secondary blended product from the sand not used in generating the primary product, and a residual product not used in either of the blended products.

Classifying tanks can perform certain functions that a sand screw alone cannot: they can produce more than one product (with a defined particle size range) at a time and they can remove excess materials from the middle of the gradation range (whereas as sand screw can only remove excess fine or coarse material).

The primary limitation of classifying tanks is that as the feed gets coarser so do the products (and if the feed gets finer, so do the products). Therefore, the control system must be able to accommodate this; simpler control systems are acceptable where the feed is consistent. If the feed is of a variable nature, more sophisticated controls may be required to keep the product within its specification range irrespective of variation in the feed. The downside to this is that in ensuring the specification range is maintained, more material may be rejected, reducing the production rate.

Thickeners and plate or belt filter press

The new limits on water abstraction, control of effluent discharge, combined with space restrictions and concerns about lagoon stability have increased pressure for maximising re-circulation of water without the use of lagoons. As alternatives, thickeners and filter presses, are becoming more common. Thickeners have slowly rotating rakes that promote settling of suspended solids and transport solid material downwards toward a central discharge point. The process is assisted by the use of automated dosing with selected chemical flocculants. Clarified water overflows at the top of the tank and is recycled. The sludge from the thickener is either sent to a silt lagoon for further consolidation or directed to a filter press that can squeeze the sludge to remove remaining water and produce a dry filter cake.

Key finding
Installing a thickener generally reduces the need for four or five silt lagoons down to one lagoon. Installing a filter presses may eliminate the need for a lagoon at all

Thickeners can substantially reduce the volume of slurry requiring subsequent handling, reducing it to less than one tenth of the volume of unconsolidated sludge in a silt lagoon. The solids content in thickener sludge is also significantly higher than in a silt lagoon, with 40% solids easily achieved. Thickeners are available to deal with a wide range of flows, from less than 10 up to several thousand cubic metres per hour (Photos 24, 45 & 46). Operating costs per cubic metre treated are generally low, but may exceed the direct and most obvious costs associated with silt lagoons. The capital cost of a thickener will also generally exceed the cost of developing a silt lagoon to deal with the same flow. However, there may be other good reasons beyond the obvious financial costs for opting for a thickener (such as land availability, concerns about sterilisation of aggregate resources, the need to rapidly recycle clean water, health and safety or environmental concerns associated with lagoons).

Key finding
Wharf operations (for processing marine sand and gravel) may adopt the use of thickeners and press filters to treat the silt and clay, saving space and recovering a large proportion of the water for recycling back to the washing plant.

Thickeners are compact relative to silt lagoons handling the equivalent flow and are useful where land availability is limited or where health and safety risks or maintenance issues for a silt lagoon are unacceptable. More importantly, they can make a significant contribution to rapid recycling of clean water, which is increasingly important as water availability becomes more limited. In these cases, thickeners and press filters may be viewed in a more competitive light despite their higher capital cost.


Photo 24. Washing plant thickener


Photo 45. Silt thickener


Photo 46. Flocculant dosing system

Key finding
Ultimately lagoons may become a thing of the past due to increasing restrictions on water.

The flocculant-treated slurry is continuously introduced into a sludge bed in the main thickener tank, where settling and consolidation occur, to form a thick concentrated sludge . The clarified (clean) water is discharged over the top of the tank, from where it can be recycled or discharged from the site. Concentrated solids are removed from the thickener by pump and can be transferred to a settling area where the material can continue to dewater and dry. However, the use of filter presses can completely eliminate the need for settling areas or silt lagoons and promote rapid recycling of a majority of water used in the washing plant via a closed circuit (minimising the need for top-up water).

Key finding
There are cost savings associated with switching from silt lagoons to a thickener or filter press system. The main one relates to waste handling, with 95% reductions possible (e.g. from £1000 for the removal of wet silt to £50 for the removal of the equivalent volume of filter cake).

Belt filter presses consist of a continuous filter screen belt constructed of a woven manmade material (Photos 47, 48 & 49)[351]. Wet slurry is distributed evenly on the filter material, which is then passed through a series of rollers that squeeze the water out, with the water passing through the woven material to be collected for recycling or discharge. At the final end drum the filter cake is removed from the filter belt by scraper and collected for use or disposal. The clean filter belt is then recharged with fresh slurry, and so the process continues.


Photo 47. Belt filter press discharge


Photo 48. Filter cake from belt press


Photo 49. Water recovered by belt press

Plate filter presses are a batch process involving the formation of a hard and stable cake under pressure (Photos 25, 50 & 51). Fully automated press filter systems are available that have automatic cloth washing and assisted cake release to minimise downtime. Compared to the settled solids present in silt lagoons, cake produced by filter press is more easily handled for disposal or further processing due to the low moisture content (less than 10% in some cases) and higher density.


Photo 25. Filter cake from plate press


Photo 50. Plate filter press


Photo 51. Plate filter press close-up

Key finding
Choosing the correct filter press is important. Too much clay in the silt slurry can cause blinding of the cloths, making them impermeable. This in turn creates back-pressure that triggers the machine to release the filter cake too early, before it is sufficiently solid.

Production + Process Technology		Table 4
Characteristics of belt and plate press filters		
Characteristics	Belt press	Plate press
Process type	Continuous	Batch normally 2 to 3 cycles per hour
Capacity	Capacity depends on belt width and speed	Capacity for each cycle depends on the plate area multiplied by number of chambers. Cycle length depends on moisture content of feed
Feed requirements	Does not require pressurised feed	Feed pressurised to 7.1 kg / cm^2 (7 bars) or 15.3 kg / cm^2 (15 bars)
Example sizes	Smaller: 1 m belt width at 3.5 tonnes per hour (tph)	Smaller: 2 m^2 plate area x 1 chamber
	Larger: 3 m belt width at 22 tph	Larger: 1500 m^2 plate area x 60 chambers or more
Maintenance	Contains many fittings, but can be fitted with automatic greasers; maintenance is generally not complicated	Fewer moving parts, but requires plates and cloths to be in good condition to work at optimum level
	Belt must be kept at the correct tension and tracking (can be	Requires less continuous monitoring

	automated)	
	Belts are washed continuously by spray bars just before the new feed	Plate cloths require cleaning at least once per week using pressure washer or automated
	Generally cloths last longer	Generally cloths wear out more quickly
	Life depends on quality of construction and maintenance	Life depends on quality of construction and maintenance
Product / output	Generally wetter filter cake (3% to 5% more moisture) but depends on feed moisture and speed	Generally drier filter cake but depends on feed moisture and length of cycle.
	Adjustable feed rate, slower speed will result in drier cake but lower capacity	Only cycles when full so reduced feed rate means less cycles per hour.
Capital and operating costs	Example capital cost = £65,000 to £70 000. Generally, anything less than 10 tph is less expensive than plate press	Example capital cost: £180,000 £200 000. Automated washing machine would add approximately £35,000.
	Needs flocculant at 0.5 kg per tonne of solids at a cost of £2.40 to £4.00 per kg	No flocculant required, but may need lime if the silt is clay-rich
	Pump size: 15 kW for 10 tph unit	Pump size = 37.5 kW for 10 tph unit, (because it works at pressure)
	Pump costs are lower open ended feed, not at pressure, lower height	Pump costs are higher greater pressure, higher off the ground.
	Infrastructure costs lower machine just high enough to fit a conveyor underneath to collect the filter cake	Infrastructure costs higher machine needs to be raised up and requires a more robust filter cake collector
Water recycling	Filtered water recycled in closed circuit	Filtered water recycled in closed circuit

Silt lagoons

The separation of the fines and water mixture generated by the washing plant is essential before the water is recycled, reused or discharged off-site. One common option is the use of silt lagoons where the solids are allowed to settle under gravity or with the aid of chemical flocculants.

Silt lagoon can include lined or unlined excavated areas (below ground level), bermed areas (above ground level) and sometimes for small volumes of water manmade tanks (Photos 26, 42, 52 & 53). The preferred shape of silt lagoons is generally rectangular, with a length to width ratio of about 5 to 1 in order to prevent short-circuiting (the fast passage of solids through the lagoon without settling). A relatively narrow width also facilitates easier removal of accumulated sediment from the longer sides of the rectangle. The distance between inlet and outlet in each lagoon should be maximised, giving the suspended solids the maximum time to settle out of the water.


Photo 26. Discharge into silt lagoon


Photo 42. Silt lagoon

Although the design can vary, they all work by slowing the flow of surface waters to facilitate the settling and consolidation of suspended solids. Their use may be constrained by land availability and site topography. Typically, they comprise one or more linked voids, developed in areas of prior working or in areas that have been set aside for water treatment. The volume of water and its suspended solid content determines the rate of filling (that is, the solid mass flow into the lagoon). If used, silt lagoons typically treat water from multiple sources (e.g. washing plant and contaminated run-off) and are designed based on the total volume of water likely to require treatment.

Key finding
Some sites use silt lagoons to treat water from the washing plant and once full they are restored and revegetated rather than being cleared of sediment and reused.

A common approach is to construct two or more ponds in series so that the water becomes progressively cleaner as it passes from lagoon to lagoon, with the coarsest material removed by the first pond, and the finer suspended solids by the subsequent pond(s). This also allows one or more ponds to continue operating while another is being cleaned out. If a lagoon is over a certain size or raised up above surrounding land then it will need to be registered with the Health and Safety Executive and its design and geotechnical stability assessed.

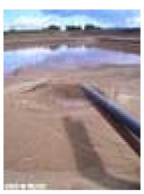
Photo 52. Silt lagoon discharge point


Photo 53. Silt lagoon at hard rock quarry

Key finding
Silt lagoons need to be of a sufficient volume to allow the silt particles to settle out and this becomes more difficult as the lagoon becomes full.

Water in silt lagoons may percolate through the base and be lost to the water table. If water is recycled from the silt lagoon, this water loss (and water lost through evaporation) will need to be replaced by top-up water.

Flocculants can be used to promote the aggregation of (ultra) fine particles, accelerate settling, facilitate dewatering and reduce the lagoon size required to treat a certain volume of water. Ideally they should be added via automated dosing stations to minimise chemical costs, reduce the risk of overdosed chemical being transferred to the lagoon discharge and because excess use can have a detrimental effect on settling. Flocculants may be particularly important during storm events when discharge quality can deteriorate rapidly.

Key finding
Operators realise that silt lagoons are not a cost free option. They have to be fenced and maintained. There is a safety risk that needs to be managed and if they have to be emptied there is a cost associated with that.

The decant rate in silt lagoons needs to be low to minimise water currents and allow sufficient time for settling to occur. The lowest decant point should be set so that the non-decanting volume is about 30% of the total lagoon volume (i.e. only 70% of the pond volume is live storage). If they are to be reused, lagoons should be cleaned out when the sediment level reaches about 20% of design volume. The need for sediment removal should also be reviewed after every major storm event or sustained period of heavy rainfall.

Key finding
There may be delays in restoration of silt lagoons while the silt dries out. The length of time needed for this will vary depending on the level of the water tablesome former silt lagoons will never fully dry out.

Where possible forebays should be used for silt lagoons. These are designed to slow water entering the main lagoon and should be around 10% of the total volume of the lagoon and 0.5 1.0 m deep. Water should enter the forebay at right angles to the weir that feeds into the main lagoon. The forebay helps slow water and promotes quiescent (stilling) conditions in the lagoon. A completely level and non-erodable (concrete) spreader should be installed between the forebay and lagoon to act as a weir and to further dissipate the water flow energy across the full width of the lagoon.

Baffles can be positioned to modify water flow and minimise the areas that are not effectively settling solids and the recirculation or re-suspension of solids. The correct placement of baffles can also assist with increasing the effective distance between inlet and outlet. Baffles that can be easily removed will facilitate periodic clearing of sediments.

When appropriate, floating discharge points should be installed. These take water from the top of the water column (where suspended solids are at a minimum). They also allow constant discharge rather than discharge only when the pond level reaches a fixed height discharge point.

The installation of automated suspended solids monitors and stop valves at the discharge point should be considered (to ensure that no out-of-specification water is able to leave the site, instead being held in the silt lagoon).

Where space is available, the presence of reeds or other aquatic vegetation in lagoons can enhance the removal of suspended solids by slowing the water and physical filtration by the plant roots. In general terms wetlands can be described as areas flooded or saturated by surface water or groundwater often or long enough to support those types of vegetation and aquatic life that have specially adapted to saturated soil conditions. Constructed or engineered wetlands attempt to duplicate natural systems and can be designed using settling ponds and lagoons as their starting point. Natural generation of reedbed and wetlands can occur in suitable settling ponds and lagoons, leading to low maintenance, self-sustaining systems. Artificial or accelerated promotion of reedbed and wetland species may be labour intensive until the systems are established, and may require specialist assistance in design and maintenance. It is important to note that not all sites will be suitable for reedbeds or wetlands. In the quarrying sector many of the additional benefits presented by reedbeds and wetlands (e.g. removal of dissolved inorganic and organic contaminants) may be largely irrelevant, reducing the financial case for specific construction. Reedbeds and wetlands will therefore rely on an existing need for settling lagoons in the majority of cases.

Due to the plastic nature of the settled sludge, the area of the lagoon may have restricted land uses after the aggregate operation has closed. For example if any construction with load-bearing structures is planned, complete removal of the sludge may be necessary.

However, with proper planning lagoons can be designed for restoration to a wide range of habitats, as part of landscape improvements and for other beneficial end-uses.

Technology: Dry Processing

Production processes in quarries can be broadly divided into two categories: the dry production of crushed rock aggregate and the wet production of sand and gravel. However, increasingly there is a crossover of production practice; the most significant being the adoption of washing plant processes in crushed rock production to reclaim usable stone from scalpings. Dry processes have made little inroads into sand and gravel operations, aside from the use of crushers to process oversize material into saleable crushed rock aggregate. Due to the pressure on water resources and the advent of time-limited abstraction licences a consideration of dry alternatives for fines removal from sand and gravel is appropriate.

Drying

Drying is the process of reducing the moisture content of material by the application of heat to evaporate all or part of the water. This is carried out to facilitate further processing of feed material, to improve the handling of products and reduce the transportation costs. Drying is an essential operation in the chemical, agricultural, biotechnology, food, polymer, ceramics, pharmaceutical, pulp and paper, mineral processing and wood processing industries. It is an energy-intensive, expensive, operation due to the high latent heat of vaporisation of water and the inherent inefficiency of using hot air as a drying medium.

Key finding

In the developed world, industrial drying operations account for anything between 10 and 25% of national energy consumption. The major costs for dryers are in their operation rather than their capital costs.

Drying occurs by the transfer of heat to the wet feedstock; the most common is by convection (over 85%), other types include the use of conduction, radiation or electromagnetic fields. Convective heating is the focus for this brief review. The first stage of drying is the removal of free, surface, or adsorbed water; the second stage is the removal of the residual, absorbed water. Heat is supplied to the boundary of the material and diffuses into the solid by conduction. Water travels to the boundary by either liquid or gaseous diffusion and is removed by the surrounding air. The residence time of material within a dryer is dependent on the rate of diffusion of water from the core to the surface of the material.

Dryers can be classified by the following criteria:

- mode of operation: batch or continuous;
- heat input type: convection, conduction, radiation or electromagnetic;
- state of material in dryer: stationary or moving/ agitated/ dispersed;
- operating pressure: atmospheric or vacuum;
- drying medium: air, superheated steam or flue gases;
- drying temperature: below or above water boiling, below water freezing;
- relative motion between drying medium and material: co-current or counter current;
- number of stages: single or multiple;
- residence time: short (<1 minute), medium (1 to 60 minutes) or long (>60 minutes).

In the quarrying industry, convective, direct-heat, continuous dryers are the type most commonly used e.g. rotary dryers and fluidised bed dryers. These are primarily used to dry asphalt plant raw material. Dryers incorporate feeding and material handling equipment, a combustion system, fuel-handling equipment and dust collection and may also include a cooling system.

The hot air is produced by indirect-heating or direct-firing; temperatures are typically in the range 100 to 200^{o} C, with temperatures as high as 450 to 550^{o} C in some dryers. The evaporated moisture is carried away by the drying medium. These dryers have a relatively low thermal efficiency; a significant proportion of energy is lost in the dryer exhaust and there is no cost-effective means of recovery. Indirect dryers supply heat to the material by conduction; the heat transfer medium is typically contained in an outer shell.

Dryers are not normally insulated, unlike kilns, which are lined with refractory bricks that protect the mechanical parts from the high temperatures used during processing. A key issue in thermal processing is the input in calories per tonne processed.

Key finding
Systems for recovery of heat are used in kilns but not with dryers; this leads to poor thermal efficiency and a perception that drying is a prohibitively expensive process.

The efficiency of the dryer is a function of the differential between the inlet and outlet exhaust gas temperatures; in rotary dryers it is also influenced by the design of the flights and the speed of rotation of the dryer.

Rotary (cascade) dryers

Rotary dryers are commonly used in the minerals industry to dry a range of commodities including clay, gypsum, kaolin, limestone, mineral sand, potash and silica sand (Photo 54). They consist of a relatively long cylindrical shell, which ranges from 0.6 to 5 m in diameter and from 5 to 30 m long, supported by two riding rings running on a set of rollers (rotation speed up to 25 rpm). They are slightly inclined from the horizontal; the slope enables material to move from the feed to the discharge end under gravity. They are suitable for a wide range of materials with varying size and composition. The feed rate ranges from less than 1 tonne to 500 tonnes per hour. Internal lifters, or flights, are used to lift, distribute and transport the material. This produces a shower, or cascade, of wet feed material through the hot gas stream, which promotes evaporation of the moisture and breaks up lumps to produce a more uniformly dried material. The hot air is introduced either at the feed end such that it moves in the same direction as the material (co-current) or at the discharge end such that it moves in the opposite direction (counter-current). The co-current direct-heat rotary dryer is the most common; wet material is in contact with the hot gas stream as its highest temperature, which causes rapid evaporation of surface moisture. As it progresses through the dryer, heat energy is lost to the material it is drying and it leaves the dryer at a comparatively low temperature. In co-current dryers, the initial heat transfer is high, which causes a considerable drop in temperature thus preventing overheating of the material and the dryer itself. The final dried product is discharged with the gas stream at its lowest temperature, which ensures the moisture content can be readily controlled. Counter current dryers are more suitable for material that must be dried to very low moisture contents or where the last traces of moisture are difficult to remove.


Photo 54. Rotary dryer

Fluidised bed dryers

Fluidised bed dryers consist of a bed of fine-grained solids, which is fluidised by the upward passage of hot air. The bed has the appearance of a vigorously boiling liquid and it takes on some distinctly fluid-like properties; this means that fluidised bed dryers operate with few moving parts. The hot air is supplied to the bed through a perforated distributor plate and flows through the bed at a flow rate sufficient to support the weight of the particles in a fluidised state. The flow rate is such that only the very fine-grained material is removed by the dust collection system. The boiling appearance is caused by the formation and collapse of air bubbles within the fluidised bed. Fluidisation ensures uniform temperature conditions with a high heat flow, thorough mixing and product consistency, removal of dust (from material such as quarry fines) and avoids overheating of the material. Conveying of the material through the dryer is either by vibration or a low frequency, high-amplitude shaker mechanism; a high mass transfer is achieved aided by the fluidising air. Fluidised bed dryers have a throughput capacity up to 300 tph. The optimal particle-size range is 250 mm to 1 mm, with a maximum of 6 mm. They have found increasing use in sand processing, particularly in the drying of sands for use in Dry silo mortar.

Indirect dryers

Indirect dryers are used where the material to be dried cannot come into direct contact with the hot air or other drying media. Indirect heating avoids contamination of the material. They are also used where the material is very fine grained or of low density. Steam tube dryers have tubes running the length of the rotary drying chamber, indirect fired rotary kilns have an outer shell for the drying medium and indirect fluidised bed dryers use steam tubes in the material bed. Removal of moisture is by use of a vacuum or a small purge of air or inert gas.

Air classification

Air classification is a process used to separate material according to its particle equivalent diameter (controlled by its density, volume and surface characteristics) using a flow of air (Photos 55 & 56). It is an approximate sizing process [352] ordinarily used to separate coarser from finer material; the size at which separation occurs is known as the cut point. This is an alternative to screening which is the standard means of sizing material; however it is inefficient below 250 micron, especially for dry material. In the sand and gravel industry, size classification of fine material is typically carried out using wet separators such as screw and bucket-wheel classifiers, hydrocyclones and other hydraulic classifiers. For further details on washing plants click here. Air classification is used in the chemical and agricultural industries to grade granular materials. In the mineral industry, it is used for sizing powders with cut points in the range 5 to 100 micron [353]; mineral industry commodities processed using air classification include calcium carbonate, cement, diatomite, feldspar, gypsum, kaolin, lime, mica, perlite, phosphates, silica sand and talc.


Photo 55. Laboratory air classifier


Photo 56. Pilot-scale air classifier

Particles introduced into a rising air current are carried upward or drop downward; the main factors are particle size and density. The airflow velocity required for a separation can be calculated from Stokes Law; this can be used to determine the velocity of air (otherwise referred to as the air drag force) required to carry away particles finer than the cut point. If the drag force exceeds the opposing gravitational force the particle is entrained in the airflow and reports to the fines product; if the drag force is lower, the particle reports to the coarse product. In theory, where the gravitational force is the same as the drag force, particles at the cut point size will be suspended indefinitely in the separator. In practice, there is a 50% likelihood that these particles report either to the coarse or fine product. A more appropriate definition of the separation cut point is the particle size where the gravitational (plus centrifugal) force is the same as the opposing drag force. This simple grading of particles using an upward flowing streams of air is known as elutriation. This process does have its limitations and is only effective for particles (density 2.7 g/cm^3) in the size range 10 to 60 micron. Centrifugal forces can be used to enable separations at cut points below 10 micron. This supplements the gravitational force to overcome the effect of the drag force on fine particles; this is the basis for the operation of dynamic air classifiers. Centrifugal separators can impart a force 500 to 2000 times greater than achievable using gravitational force alone (Buell, 2006).

A classifier sizes particles according to their settling velocities in air; several factors affect particle settling velocities other than particle size. The density can cause small particles to behave as larger particles; a 53 micron particle with a density of 4 g/cm^3 will behave in the same manner as a 75 micron particle with a density of 2 g/cm^3. Particles with a high porosity will have low apparent density and this has the effect of increasing the effective cut point size. Particle shape also affects classifier performance, especially when it deviates significantly from a spherical form.Flaky particles will tend to report to the fine product due to their large surface area.

Key finding

Material dispersion is critical for efficient separation; particle agglomeration results in the misplacement of fines into the coarse product. High moisture content is the chief cause; it should be less than 0.51% to avoid this problem. The airflow can be heated to enable drying of material during classification.

There are two categories of air classifier; static (gravitational) and dynamic (centrifugal or mechanical). These use the separation principles of counterflow or crossflow; this refers to the passage of the material, which is either opposite (counterflow) or across (crossflow) the main airflow. In gravitational-counterflow separators, particles experience the downward pull of gravity and the uplift due to airflow. In gravitational-crossflow separators, horizontal airflow carries particles until they drop out or are carried through the outlet. Particles are graded within the separating chamber with coarse particles close to the inlet and finer particles closer to the outlet. In centrifugal-counterflow separators, airflow is fed tangentially into a cylindrical or cone-shaped chamber forming a vortex. Coarse particles are thrown outward and migrate to the outlet at the base. Fine particles are entrained in the airflow and migrate to a central outlet. In centrifugal-crossflow separators, an air vortex is created in a cylindrical chamber with the inlet and outlet placed on opposite sides of the chamber. Coarse particles report to the lower outlet and fine particles are entrained in the airflow and migrate to an upper outlet.

Static gravitational classifiers

These consist of air flowing through a separating chamber with product outlets for coarse and fine products; there are no moving parts in the separation chamber. They are typically limited to coarse classification with cut points in the range 212 micron to 1.7 mm, although this can be extended to 75 micron. Early classifiers consisted of vertical chambers with an upward moving airflow or winnowing machines that use the gravitational-crossflow principle; however these suffered from poor separation efficiency. Cascade air classifiers are a development of the vertical classifiers, with varieties such as the zig-zag and shelf classifier. In these, separation efficiency is improved by disrupting the flow of material as it falls through the chamber; air vortexes in the chamber improve the separation.

Fluidised bed classifiers employ the gravitational-counterflow principle; a fluidised state is created by forcing air up through a bed of feed material and fines are removed in the airflow. Coarse particles remain in the bed of the separator and are removed through the outlet. Fluidised bed classifiers have higher recoveries of fines than other classifiers; this may be a function of the longer residence time in the separator. They also have the sharpest separation of the static classifiers; cut points are achievable in the size range 50 micron to 1 mm.

Dynamic classifiers

These usually consist of cyclones (conical separation chambers) either with or without the assistance of mechanical rotors. They generally employ the centrifugal-counterflow principle; some air classifiers of this type employ a combination of both gravitational and centrifugal separation. They enable finer separations than static classifiers, with a greater degree of cut point control and higher recoveries. Classifiers employing centrifugal force can achieve separation cut points in the range 5 to 100 micron (sub-micron sizes with some classifiers). Dynamic air classifiers are often integrated into dry grinding mills. The efficiency of dynamic air classifiers is influenced by different factors such as centrifugal force, drag factor, particle concentration and air flow conditions (including the inlet and outlet areas).

Vortex, or spiral, air classifiers usually consist of single or double cones; stationary inclined vanes or adjustable blades are often used to create a vortex in the airflow. The feed is entrained in the airflow and introduced into the separator via a tangential inlet into the top of the chamber or an inlet at the base of the chamber. Single cones are used for coarse classification whereas double cones can be used to remove material finer than 75 micron. Rotor classifiers contain rotating blades that create cyclonic air circulation within the separator; these are mounted on vertical or horizontal shafts. The speed of rotation and airflow velocity are the main process factors. Circulating air classifiers are widely used in the cement industry; these consist of a double-cone separating chamber. They have a high volume throughput (up to 800 tph) although controlling the desired cut point is difficult.

Process performance can be described in relation to the particle-size distribution of the feed material and the classification products. Feed material is separated into coarse and fine-grained products at a given cut size. Due to various random factors (such as air turbulence and interparticle collisions) some fines are separated with the coarse product and vice versa. The quality of the products can be defined by the proportion of expected particles, such as the proportion of coarse particles in the coarse product; this is known as fractional cleanness. Correspondingly, the proportion of unwanted particles, such as fines in the coarse product is known as fractional dirtiness. Other process factors include the product yield, which is the mass of a product relative to the feed and the fraction recovery, which is the ratio between the masses of any fraction in a product and in the feed. The latter characterises the separation efficiency; for example, 90% efficiency would relate to 90% of the mass of fines in the feed reporting to the fines product. Improvements in air classifier design and separation efficiency have focused on creating a stable, well-defined airflow, reducing turbulence, eliminating particle collisions, controlling the feed and multiple classification stages.

Industrial up-take of air classification

Air classification has yet to be taken up in any significant way by the UK aggregates industry. It is used by some aggregate companies, for the production of higher-value industrial mineral products, such as mineral fillers, dry silo mortar and cement. This is particularly the case with limestone quarries and a few sandstone quarries. However, the higher value of these products enables the use of higher-cost processing options.

Key finding
*The most likely use of air classification in the UK quarrying industry will be for the removal of material finer than 63 microns from fine aggregate or quarry fines to produce manufactured sand. This is already the case in some quarrying operations in the USA. Further details on quarry fines and waste are available **here**.*

The motivation for using air classification, rather than the more traditional wet processing option, will be the increasingly restricted access to water, and the costs of mitigating the environmental impacts associated with its use. Currently, there is a widely held perception that air classification is an expensive process to install and operate, particularly as there is a need to dry material before it can be processed. The future development of more efficient drying technology will reduce the costs of drying. Further details on Future Technology are available here.

Technology: screening

Screening

Screens play an important role in the operation of almost all mineral processing plants (Photos 57, 58 & 59). The correct selection and design of a screening system will have an important impact on the efficiency of an operation. Screens can be divided into static and dynamic (vibrating) screens. Vibrating screens are typically employed for applications above 2 mm and therefore are commonly found within crushing plants. Screens are used to remove material that is already fine enough for the next processing step. This reduces the load on the crusher, enhances reliability by reducing packing on the screen and improves energy efficiency. Avoidance of unnecessary crushing also contributes to fines minimisation, maximising the production of saleable material . Screening is also used to produce closely sized products.

 Photo 57. Wash jets over wet screen

 Photo 58. Wet screening gravel

 Photo 59. Dry screening crushed rock

Importance of screen vibration

The deck of a screen is vibrated to produce stratification of material on the deck surface. Finer particles pass through the bed and meet the deck surface. Particles much smaller than the screen aperture dimension have a high probability of passing through on any contact with the deck. For particles of dimensions approaching that of the screen aperture the probability of passing through on contact is lower, and a greater number of opportunities (or trials) must be given to improve screen efficiency. In practice, screening plants are normally designed to operate at 90-95% efficiency.

Screening efficiency

A number of different definitions of screen efficiency have been proposed depending on whether the screen is producing oversize as a product (efficiency of undersize removal) or undersize as a product (efficiency of undersize recovery). Most screen manufacturers use undersize recovery as a measure of screen efficiency. Industrial screens are typically designed to give 90-95% screen efficiency.

Key finding
Inefficient screening can result in the unwanted presence of fines in aggregate products, increased loading on crushers and increased fines production as undersize is recirculated for crushing.

Wet or dry screening?

Wet screening is typically considered when the feed material has a high moisture content (39%), when screening at fine sizes (-5 mm) and when fine particle agglomerates are present such as clay balls. Wet screening can improve screen efficiency by helping to transport fines through the aperture, removing build-up on the screen surface and reducing blinding. The more dilute the feed the more efficient will be the process, with addition of spray water assisting the separation. It can also assist with dust suppression but may increase corrosion if wire screens are used.

Types of screen

Fixed or stationary screens

A fixed, inclined grid can be used to prevent oversize passing to all or part of a processing plant. An example of a screen that can be operated in stationary mode is a grizzly screen commonly used to scalp material prior to a primary crusher. In its simplest form it can be made from stationary bars aligned in the direction of flow. To minimise the problem of clogging the bars may taper with an increasing gap at the discharge end.

Sieve bends are fixed screens that can be used for very fine wet screening operations. The sieve bend has a curved screen composed of horizontal wedge bars. Feed slurry flows tangentially over the screen surface assisting transportation of oversize. The separation size achieved is approximately 50% of the aperture width, a feature that contributes to reduced blinding of the screen surface.

Vibrating screens

Vibrating screens have one or more screen decks, mounted one above the other, with each deck having a smaller aperture then the one above it. The whole assembly may be horizontal or inclined from feed to discharge. According to Napier-Munn *et al*[356] vibration is induced by means of eccentric counter-weights on a lateral rotating shaft, eccentrically mounted shafts, or eccentrically counter-weighted motors. The choice of mechanism will control the type of screen motion that causes movement of the particles (both vertical and horizontal) on the screen. Vertical movement helps to dislodge particles that have pegged the apertures, hence increasing the screen area available. Horizontal movement ensures that particles are presented in different positions on the screen surface. The types of motion that are most common (Fig. 2) are:

i) Circular motion with inclined decks. Typical inclination is 20°. Gravity assists with transportation. The stroke and direction of rotation influence screen performance. Commonly used for coarse sizing (Screen Operation animation below).

ii) Low angle linear motion screens. Typical inclination is 0 to 10°. Motion is usually directed at 40 to 45° to the screening surface. Larger throws are necessary to enhance transportation by gravity. Commonly used for fine sizing and washing, where the lower bed depth is an advantage.

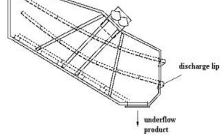

Figure 2. Double deck banana screen

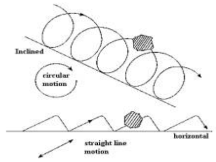

Figure 3. Screen motions

Mellor [355] provides more detail on the design of vibrating screens that can be further categorised into inclined two-bearing, inclined four bearing and variable ellipse screening units. One hybrid-type screen used in the minerals industry is the multi-angle or banana screen (Figure 3). This has a stepped deck arrangement that is typically angled at 20 to 30° at the feed end and 10 to 15° at the discharge end. The advantage of this design is that fines are quickly removed at the feed end that has a fast flowing low bed depth, while near-size material can be separated at the discharge end with its lower flow-rate and thicker bed depth.

Rotary Screens

Rotary screens (trommels) are screens of perforated steel plate are assembled into a tubular arrangement and rotated. This screen has largely been superceded by the vibrating screen because of its low capacity. It still may be used as an initial dewatering ring at the discharge end of a washer barrel.

Probability screens

Probability Screen, such as the Mogensen Sizer, uses a multi-deck configuration, with each deck mounted at an increasingly steep slope angle from top to bottom as the aperture size is reduced. Each short deck (3, 5 and 6 deck options are available) which are of equal length, only pass particles that are typically less than 70% of the aperture size. This property helps to reduce the problem of screen pegging. A very high specific throughput, while maintaining acceptable screen efficiency, is claimed by the manufacturer. The screen deck surface A range of different screen surfaces is used in practice. These include:

- *Woven wire.* Offers a high open area and good screen efficiency. Has a high wear rate with abrasive materials.
- *Wedge wire.* Comprises wedge-shaped parallel members with small separations, usually mounted cross-flow. Is typically used for dewatering or fine separations.
- *Punched plate.* This is stronger than woven wire giving a longer life. Different aperture shapes are possible.
- *Rubber.* Decks are moulded with reinforcing (steel wire cables etc.). It gives good wear resistance and has a lower open area than wire screens.
- *Polyurethane.* Gives good resistance to sliding wear which is particularly important in fine screening and dewatering operations. Modular screen panels are typically used. Relatively easy maintenance panels are light and only worn panels need to be replaced. Open area lower than for steel screens.

Aperture shapes and open area

Screen open area is an important design parameter (Photo 60). It can be defined as the percentage of the screen surface that is aperture. Care should be taken as fixings and borders may result in the screen open area being significantly lower than the individual panel open area. Some of the aperture shapes available are shown in Figure 4.


Photo 60. Close-up of screen apertures

- *Square apertures* are the most commonly used offering accurate sizing; good wear life with reasonable open area.
- *Round apertures* provide a strong deck surface that is used in some heavy-duty applications where crushing and wear is likely. The open area is however lower than for square apertures and the deck surface is more prone to pegging. Rectangular or slotted decks provide a means of increasing the open area of a deck and can reduce the incidence of pegging or blinding.
- *Rectangular apertures with flow* are ideally suited to screening regular shaped particles, but are not suitable for flaky material where very accurate sizing is important
- *Rectangular apertures across flow* are suited to applications where pegging is likely to occur.

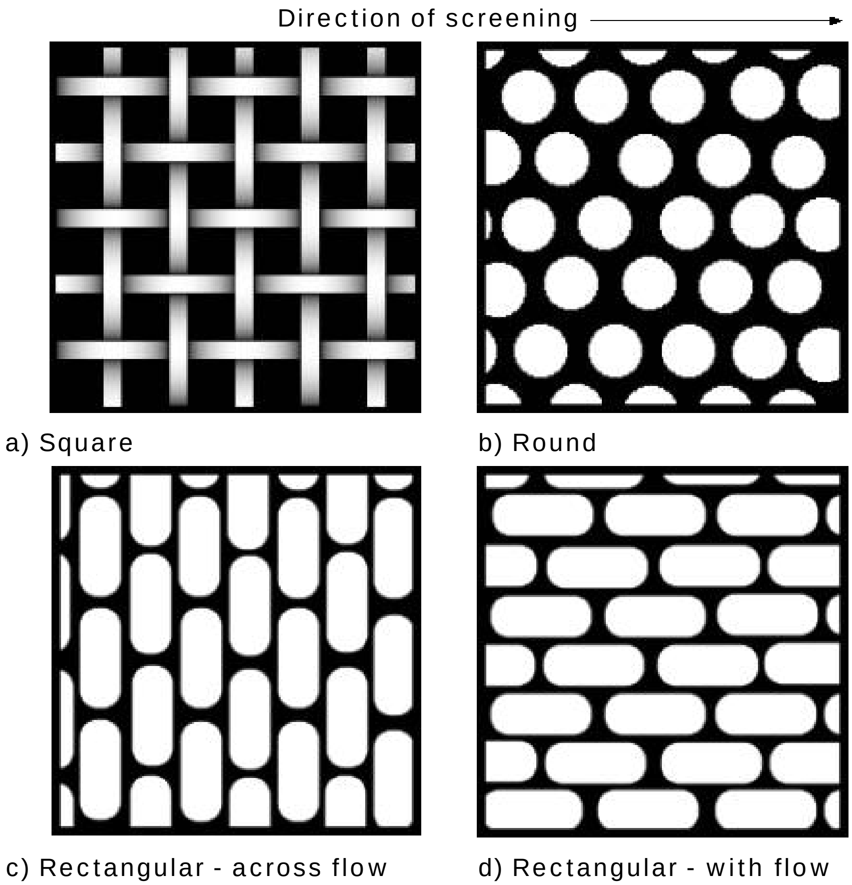

Figure 4: Common aperture shapes used in comminution circuits (after Napier-Munn 356).

Future Technology and Practices

Future production trends of the UK quarrying industry will be guided by economic and legislative developments with increasing emphasis on energy and water consumption, recycling and waste generation and disposal issues. Climate change is a key driver; it is likely to have a significant direct and indirect impact on the aggregate industry. Current scenarios indicate that average global temperatures will continue to increase. In Britain results could include more frequent and severe heat waves, drier, warmer summers, milder, wetter winters, and more extreme weather events including extreme rainfall. Direct impacts are therefore likely to include water shortages and/or water excesses. However, in some respects it is the indirect impacts that are likely to be more significant. The strategic response to greenhouse gas emissions and climate change will drive the agenda for energy supply and consumption and also the management of water supplies for the foreseeable future. As the quarrying industry is a major user of energy and water, voluntary and regulated responses to climate change will affect its consumption of energy and water.

Carbon neutrality and offsets

Growing awareness of the risks of climate change has propelled national and local governments, companies and NGOs to take action to manage greenhouse gas (GHG) emissions, including the introduction of carbon offsets and tradable quotas or ‘caps’. At an international level, the main instruments driving the market in GHG emissions are the Kyoto Protocol of the United Nations Framework Convention on Climate Change, which has been ratified to date by 163 countries, and the Emissions Trading Scheme of the European Union.

Carbon brokers such as CO_2e (www.co2e.com), EcoSecurities (www.ecosecurities.com) and Natsource (www.natsource.com) are also becoming increasingly prominent as trading via GHG-related exchanges such as the Chicago Climate Exchange (www.chicagoclimatex.com) and Greenhouse Gas Exchange (www.ghgx.org) continues to increase.

Aggregates and carbon trading

The energy used to produce a tonne of aggregate is equivalent to approximately 10kg of CO_2; the current cost of offsetting this CO_2 is 7 Euro cents or 4 pence (based on the current carbon exchange trading price for a tonne of CO_2 which is around €7 or £4.70). Offsetting typically involves tree planting, occasionally in old quarries; one tonne of aggregate would require the planting of one tree. Based on the annual production of aggregate in the UK this would require the planting of 281 million new trees. The CO_2 figures are purely based on production and do not consider transportation or ultimate enduse.

Currently, assessment tools used to determine CO_2 emissions assume that the same amount of energy is used to produce both primary and recycled aggregate. However, it is likely that more detailed information arising from life cycle inventories and assessments may change this in favour of recycled and secondary aggregate. This will probably mean that there will be increased pressure to reduce the environmental impact of primary aggregate production; one result of this may simply be an increase in the substitution of primary aggregate for recycled and secondary aggregate. What can the UK quarrying industry do to address this situation? How long before the first carbon neutral quarry?

Energy consumption

Reducing energy consumption has always been a key target for those involved in production; however the main motivation has been controlling costs rather than addressing green issues. There are a number of energy strategies that could be applied in the future:

- *Energy efficiency* : One means of assessing the amount of energy used to produce aggregate is to determine the embodied energy (or embodied CO_2); this refers to the quantity of energy (or CO_2) required to produce and transport aggregate. Eco-friendly construction projects select the most energy efficient construction materials by auditing embodied energy. The production of aggregate requires 6 to 139 kWh of energy per tonne; ready mixed concrete, 278 kWh/tonne (largely due to the high energy costs of cement production) and recycled aggregate, 28 to 111 kWh/tonne. The figure for recycled aggregate is surprisingly high but probably reflects the proportion of cement present. It is possible that the embodied energy will become one of the important criteria for future aggregate production; especially as concern over climate change is one of the key drivers behind the sustainable development ethos of the mineral planning system.
- *Energy reduction:* Heat-assisted comminution may be a future means of reducing the energy costs associated with

aggregate production. Shock heating and rapid cooling of as quarried rock would promote rock fracturing prior to crushing. Less energy would be needed to crush the rock; this may also help to reduce the amount of fines produced. The main drawback is the amount of energy required to heat the rock; cheaper and more efficient methods of heating are needed to make this process viable. Microwave or ultrasound treatment may be a possible way forward.

- *Energy avoidance* : The use of subsurface grouting to minimise groundwater flow through the rock mass that is, or will be, extracted. This reduces the need to abstract groundwater to keep the workings dry, which may be a substantial energy consuming activity and cost at some sites.

Water consumption

A recent review by the Parliamentary Office of Science and Innovation noted that in most areas of England and Wales, the balance between water users and the environment is currently sustainable (www.parliament.uk/documents/upload/postpn259.pdf). However, in some locations, this is not the case, and excessive use of water is putting water-based ecosystems at risk. While this is not solely an issue for the aggregate sector, quarrying activities can use and consume significant amounts of water across the operational lifecycle, from initial exploratory investigations through to closure and beyond. For further details on washing plants click here. Consequently, finding new ways to minimise water use in general and water consumption in particular will become increasingly important in the short- and medium-term.

As noted elsewhere, there is an ongoing drive to reduce overall water consumption through improved recycling and reuse and implementation of good practice. The uptake of low water use / high efficiency washing systems and screens is also increasing across the sector. However, there are a number of additional options for the future, ranging from changes in practice to the use of different technologies. Examples include:

- The capture and storage of clean water entering the site as rainfall can be improved (e.g. capturing water directly from 'clean' surfaces such as plant roofs before it can become contaminated with particulates on the ground).

- 'Pinch analysis' can be applied to minimise water use and consumption. This is a systematic process analysis tool, originally designed for energy applications, but now extended to the optimisation of water network design and water treatment, recycling and reuse. Pinch analysis allows a user to benchmark their actual water consumption against a theoretical minimum. It can then be used to identify opportunities to save water and move the operation closer to its minimum achievable consumption. Pinch analysis for minimisation of water consumption is being used increasingly in the petrochemical, paper, textile and food industries, but as yet there appears to be little uptake in the aggregates sector (for an example of a case study in the chemicals sector, see www.envirowise.gov.uk/page.aspx?o=119526).

- Due to the pressure on water resources and the advent of time-limited abstraction licences it is possible that dry alternatives for fines removal from sand and gravel will be adopted. The current perception is that this will be expensive due to the high costs of drying; however, development of high efficiency drying technology may make dry processing a reality in the future.

- Inland or marine brackish/saline waters can be treated and used as a replacement for freshwater supplies.

Recycling and quarry waste

Aggregates, including sand, gravel and crushed rock, account for 80% of a typical concrete mix; the concrete industry is actively pursuing a policy of recycling concrete in order to reduce the use of these natural resources. Some construction companies are achieving a recycling rate of 70–90% of concrete from their waste streams returning as aggregate (www.sitelines.co.uk/pdfs/22103.pdf).

In many manufacturing industries, products are designed for recycling. The production of aggregate, and construction products, could possibly be modified to enable easier recycling and improve the properties of recycled aggregate. Aggregate composed of recycled concrete generally has a lower bulk density and higher absorption than natural aggregate; concrete made with recycled aggregate has at least two-thirds the compressive strength of natural aggregate concrete. This is because recycled aggregate consists of composite particles of natural aggregate and cement. Separation of the cement from the natural aggregate would enable production of a recycled aggregate with properties much closer to those of natural aggregate; the cement could be separated and used as a sand substitute. In the future, it is possible that the aggregate crushing process could be modified to produce natural aggregate that is easier to remove from concrete, has more uniform properties and can be used to produce concrete with properties similar to that made with natural aggregate. Surface modification of aggregate, using biological or polymer coatings, may be a possible way forward. By extension, modification of quarry fines and other quarry wastes using physical, chemical or biological methods to produce value-added materials for sale in specialist and bulk commodity markets might be possible.

Future trends in crusher development

Modern crushers have benefited from a better understanding of the feed characteristics, machine geometry, crushing chamber design, the relationship between power draw and crushing force, speed of operation and lubrication/ hydraulic system conditions[357]. Future developments of crushing technology will be driven by the industry focus on:

- higher productivity at reduced costs per tonne (increased profitability)
- higher size reduction ratios
- reduced stock inventory and 'just in time' supply
- improved reliability and availability of plant.

Current tends that will continue into the future include:

- *Crusher automation:* This can lead to an increase in throughput (up to 30%) compared to manual control. The use of hydraulically activated setting mechanisms allows crushers to be easily and simply integrated into partially or fully automated systems. Automation ensures that the crusher always operates within ideal parameters, promoting the constant choke-feeding condition that improves liner utilisation and inter-particle crushing required for good particle shape (i.e. cubical shape).
- *In-pit crushing:* This is already well established in the UK quarrying industry. The use of highly manoeuvrable self-propelled track-mounted crushing and screening plants has reduced, and in some cases eliminated, the need for haulage. This trend will continue and new mobile plant will be developed.
- ***Cone crushers**:* These will become smaller, quieter and more energy efficient.
- *'Smart' crushers and screens:* This equipment will become more common and performance and condition monitoring will be conducted automatically with data fed back to the operator or even to the equipment manufacturer for routine maintenance or problem solving at a distance.
- *Control and instrumentation:* Particle-size analysers will determine the size distribution and mass of a material stream, this will be used to control the crusher settings in real time

---

Future trends in drying technology

Heating and drying accounts for between 10 and 25% of industrial energy consumption in developed economies; therefore high-efficiency technologies would make a significant contribution to reducing energy consumption and cutting CO_2 emissions. Conventional drying mainly uses rotary convective technologies, which have a relatively low thermal efficiency. Potential high-efficiency drying technology includes the following:

- *Microwave heating*: This has the advantage that it enables uniform drying, requires less heating time (as low as 1% of that required by conventional heating) and microwave energy is selectively absorbed by areas with greater moisture content.
- *Pulse combustion drying*: This involves intermittent combustion of the drier fuel; this process is up to 40% more efficient than conventional dryers. Currently, this technology appears to be restricted to spray dryers, for example those produced by Pulse Combustion Systems (www.pulsedry.com); however there may be potential for this to be used for a wider range of materials in the future.
- *Insulated dryers*: These have a high thermal efficiency but a low capacity throughput; development of this technology would enable an efficient and relatively cheap form of drying.

Blue sky concepts

- *'Centre for Sustainable Aggregates'*: This could be a central research facility co-sponsored by aggregate industry, technology and service providers and other relevant bodies to specifically develop new and innovative technology and management practices (e.g. taking on work that one company or provider would be unable to fund or undertake in isolation). The facility could also have a 'cross-pollination' function, assessing and developing relevant technology and concepts used in other sectors. The International Centre for Aggregate Research (ICAR) based at the University of Texas in the USA is one model that could be followed (www.icar.utexas.edu); alongside university courses, it coordinates research projects, facilitates technology transfer and provides access to information on aggregates technology.
- *Centralised processing*: Environmental and social issues, in particular the growing pressure on water availability, are potential drivers of a radical change in how extraction and processing of aggregates are interlinked. The present standard approach is to process extracted aggregates on-site. However, local and regional water shortages, environmental and

social issues and economics may promote a move towards centralised processing in some cases (with the most likely scenario being centralised processing of material from two or more extraction sites operated by the same company). There are still, of course, substantial environmental issues in following this approach, not least of which would be transportation of material to and from the central processing hub. However, the concept may be worthy of an initial scoping study and preliminary economic and environmental cost-benefit analysis for a range of simulated scenarios.

Summary

SUMMARY OF GOOD PRACTICE: PRODUCTION AND PROCESS TECHNOLOGY

Good practice for extraction

The extraction, or quarrying, of material is by drilling and blasting, or simply mechanical excavation, followed by haulage to the processing plant by truck or conveyor.

- Overburden should be reused in site restoration; preferably direct placement where possible.
- Blasting is required for hard rock excavation; wherever possible alternatives (such as mechanical ripping or direct excavation) should be used.
- Blasting should be designed to obtain the optimum fragmentation to reduce the need for secondary breakage but without producing excessive fines.
- Unnecessary noise and vibration associated with blasting can be minimised by controlling drill hole parameters, sequential blast designs and optimising the amount of explosives used
- Sand and gravel quarries are either worked wet or dry, but dry extraction is the most efficient as it allows greater resource recovery and more selective extraction.
- Hauling of extracted rock is a significant production cost; the use of conveyors is a cost-effective alternative to trucks.

Good practice for production plant

The production of aggregate and other quarry products is carried out by crushing, washing, screening and classification. The current UK market requirement for finer aggregate products has resulted in higher fines production across the quarrying industry so quarry fines minimisation has become an increasing priority for operators.

- Production plant should be designed to meet product specifications; plant design should start with the products in mind rather than the as-quarried rock to avoid unnecessarily complicated processing and fines production.
- Crushing should be carried out in several stages with small size reduction ratios; the number of stages should be optimised to limit fines production.
- The amount of energy required to crush rock is known as the grindability or Bond Work Index; this can be used to select the most appropriate crusher.
- It is generally accepted that compression crushing produces less fines than impact crushing; to minimise fines, avoid crushing processes that have major components of attrition and abrasion.
- Attempts to minimise fines production should be focused on the later stages of production; primary crushing typically produces less than 10% fines whereas secondary and tertiary crushing produces up to 40% fines.

Good practice for crushing equipment: jaw crushers

Jaw crushers are typically used as a primary crushing stage and are one of the quarrying industry workhorses.

- Ideally, the closed side setting (CSS) should be set to give a size reduction of less than 6:1; smaller settings will produce more fines than larger settings.
- Choke feeding is preferable; this helps to reduce impact and wear on the jaw plates, minimises the top size and reduces the production of flaky material.
- Lowering the crusher speed will reduce the amount of fines produced; the trade-off will be a correspondingly lower crusher throughput capacity.
- Optimum selection of the jaw crusher throw is important as it maximises the amount of energy used in crushing; short throws are used for fine-grained, brittle, hard rock (such as basalt and limestone) and longer throws for coarser-grained, tough, more-elastic rocks (such as granite and sandstone).

Good practice for crushing equipment: gyratory and cone crushers

Gyratory crushers are typically used in primary crushing stages; whereas cone crushers are typically used in secondary and tertiary crushing stages.

- Ideally, the closed side setting (CSS) should be set to give a size reduction of less than 6:1; lower reductions may cause boiling in the crushing chamber and it should be remembered that smaller settings will produce more fines than larger settings.
- Material should be uniformly distributed as it is fed into the crusher.
- Choke feeding is preferable, typically the cone crusher is buried in feed material; this helps to reduce impact and wear on the crusher liners, improves throughput capacity, minimises top size and reduces the production of flaky material.
- Gyratory crushers tend to be more tolerant of variations in feed material and feed rate than cone crushers.
- Increasing the crusher speed will improve the particle shape and increase the throughput capacity; the trade-off is an increase in the crushing chamber residence time and higher fines production.
- Regular sampling and particle-size analysis of crusher product is useful as it indicates when liners need to be replaced.
- Cone crushers should be considered as an alternative to impact crushers especially where good (cubical) particle shape and fines minimisation are required.
- Monitoring the load on the crusher motors and hydraulic mantle adjustment system will forewarn of crusher packing problems.

Good practice for crushing equipment: impact crushers

Impact crushers are typically used as a final crushing stage to reduce the proportion of flaky material; they produce a higher proportion of fines than compression crushers.

- Feed material should be introduced into the crusher across the full width of the rotor to ensure uniform product gradings and uniform wear in the crusher.
- Higher rotor speeds will increase the size reduction ratio and fines production; slower speeds will reduce fines but also results in a poor product shape.
- Increasing the proportion of rotor feed to crushing chamber feed in VSI crushers will reduce the fines produced; the grading of the crusher product will also be coarser.
- Increasing the gap between the rotor and impact surfaces will reduce the crushing chamber retention time, reduce size reduction ratio and lower fines production.
- Screening and recirculation of oversize material will improve the aggregate particle

shape (more cubical), however closed circuit crushing increases fines production.
- Impact crushers should be replaced by cone crushers where good (cubical) particle shape and fines minimisation are required.

Good practice for washing plant

Washing is carried out to produce clean sand and gravel, or recover stone from clay-rich scalpings at crushed rock quarries; aim to remove material finer than 0.063 mm.

- All water should be recycled and reused wherever possible.
- Water consumption can be minimised by water-efficient technology; thickeners and filter presses enable the reuse of process water, and minimise the need for lagoons.
- Lower quality, recovered water may be acceptable for use in less-critical applications such as dust suppression.
- Demonstration of water efficient practice is a requirement for the renewal of time-limited abstraction licences; the adoption of waterless fines removal technology would remove the need for silt lagoons and enable the easier handling of fines.

Good practice for dry fines recovery

Dry fines recovery is carried out by dry screening and/ or air classification. Feed material requires drying, this is an energy-intensive process.

- Low moisture contents are required for efficient dry fines recovery; for the removal of fines (<0.063 mm) the moisture content should be 0.1 to 0.5 wt%.
- Centrifugal air classifiers are recommended for removal of fines; efficiency of fines removal relies on a controlled feed, stable airflow and multiple classification stages.
- Screening should be optimised to ensure efficiency; inefficient screening results in poor quality products, increased load on crushers and over-crushing.