Quarry fines minimisation:
Can we really have 10mm aggregate with no fines?

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Abstract (100-200 words)

In 2005, 216 million tonnes of saleable aggregate was produced in the UK; a corresponding 55 million tonnes of quarry fines and 24 million tonnes of quarry waste were also produced. The need to minimise fines production is driven by the Aggregates Levy (which has priced quarry fines out of the market in favour of recycled aggregate) and the Landfill Tax (which has made it expensive to dispose of fines). Attempts to reduce fines production often start with a process optimisation audit; the case study presented illustrates how fines production can be reduced, in this instance by up to 30%. Application of good practice in the crushing plant also helps to reduce fines production, including: reducing the crushing ratio to 6:1 or lower; maintaining uniform feed distribution; choke feeding (for compression crushers); reducing the speed of impact crushers; and reducing the degree of recirculation by increased screening efficiency. Future developments are likely to be driven by the need to respond to climate change. New crusher designs will be more automated, offer improved energy efficiency, have a greater production capacity and improved reliability.

Keywords: quarry fines; industrial minerals; crushing; fine particle processing; process optimisation; simulation

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 information given in this paper is a summary of that available in new sections on the GoodQuarry website (www.qoodquarry.com): 'Production technology' and 'Quarry fines and waste'.

Primary crushed rock aggregate is produced from hard, strong rock formations including igneous (andesite, basalt, diorite, dolerite, gabbro, granite, rhyolite, tonalite and tuff), metamorphic (hornfels, gneiss, quartzite and schist) and sedimentary (sandstone and limestone) rock. It is produced from quarries with outputs typically in the range of 100,000 to 5 million tonnes per annum (tpa). Primary aggregate is produced by extraction and processing to produce the desired physical properties of the end-product.

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. 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 (Table 1).

Table 1 Quarry process 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

HSI = Horizontal Shaft Impact; VSI = Vertical Shaft Impact

Products from quarries include aggregate, asphalt, industrial minerals, lime, mortar ready mixed concrete and concrete products. Aggregates are the primary output from quarries in the UK and are used to manufacture other construction products such as ready-mixed concrete, asphalt, lime and mortar. 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 from the British Geological Survey website (BGS, 2007). The quality of UK quarry products is controlled by the European standards for aggregate; information on these is available from the Quarry Products Association website (QPA, 2007).

QUARRY FINES AND WASTE

In the past, quarries produced a range of "single-size" aggregate products up to 40 mm in size. The trend for highly specified aggregate has meant that products have become increasingly finer. In the UK demand is highest for aggregate with a top size of 10mm. The decrease in aggregate size has meant an increase in the amount of fines produced; production of 40 mm aggregate results in around 5–10% fines, 20 mm aggregate, 15–20% fines and 10 mm aggregate, 35–40% fines. This paper examines the dilemma posed by the production of fine aggregate products; meeting the current demand for 10 mm aggregate results in a significantly higher proportion of quarry fines than in the past.

Quarry fines, defined by the BS EN aggregate standards, are the inherent fraction of an aggregate passing 0.063 mm (63 microns). Many quarries also refer to their (sub-economic) fine aggregate (finer than 4 mm) as 'quarry fines' or 'quarry dust'. The term is used here to denote both fine aggregate and quarry fines. The proportion of quarry fines produced depends on the:

- mineral composition and texture of the rock
- explosive energy used in blasting
- crusher types used and the number of stages
- reduction ratios used in crushing
- use of closed or open crushing circuits
- subsequent handling, transfer and transport of aggregate products

Quarry waste is generally inert and non-hazardous. It is produced from overburden/ interburden materials, from washing of sand and gravel to remove fines, and from scalping, crushing and dry screening. To some extent it has become waste because no market currently exists for it, due to its location with respect to potential markets and market economics.

Estimated annual production figures for aggregate, quarry fines and quarry waste are shown in Table 2. Total annual production of quarry fines is estimated at 55.1 million tonnes; this is based on estimates of fines production of 20% for limestone, igneous and metamorphic rock, and sand and gravel, and 25% for sandstone. The total annual production of quarry waste in the UK is estimated at 24.1 million tonnes (based on a waste to saleable product ratio of 1:9).

Table 2 Production of aggregate, quarry fines and quarry waste in the UK

Rock type	Annual production (million tonnes, 2005)		
	Saleable aggregate[1]	Quarry fines[e]	Quarry waste[4]
Sandstone	11.6	3.9	1.3
Limestone [2]	76.3	19.1	8.5
Igneous and metamorphic	46.0	11.5	5.1
Sand and gravel [3]	82.4	20.6	9.2
Total	216.3	55.1	24.1

1 Estimated aggregate production from Annual Minerals Raised Inquiry (Office of National Statistics, 2006)
2 Limestone including dolomite and chalk 3 Land- & marine-won sand and gravel
4. Estimated quarry waste modified from Defra mineral waste statistics (Defra, 2007)
e = estimated

Influence of crushing stage and rock type on fines production

The amount of fines produced increases as feed 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%. At some sites, the demand for quarry fines exceeds supply; typically, this is addressed by recrushing single-size aggregate, reducing the closed side settings (CSS) on jaw and cone crushers or increasing the feed rate to vertical shaft impact crushers. Table 3 indicates the fines content generated at each crushing stage; the proportion of fines produced varies with the type of rock and also the type of crusher used.

Table 3 Quarry fines produced in hard rock aggregate operations

Production stage	**Rock type**	**Proportion of quarry fines produced** (weight %)
Primary crushing	Sandstone Limestone Igneous & metamorphic	1 – 2% (Jaw) to 15-20% (Impact & gyratory) 6 – 7% (Jaw) to 20% (Impact) 3 – 6% (Jaw) to 10 – 15% (Gyratory)
Secondary crushing	Sandstone Limestone Igneous & metamorphic	10 –15% (Cone) 15 – 25% (Cone) to <30% (Impact) 10 – 23% (Cone)
Tertiary crushing (& subsequent stages)	Sandstone Limestone Igneous & metamorphic	~15% (Cone) to 40% (Impact) <20% (Impact) to 40% (Hammer mill) 5 – 30% (Cone) to 40% (Impact)

NB The proportion of quarry fines produced is attributed to specific crushers (in brackets)

Sandstone quarries: Sandstone quarries mainly produce crushed rock aggregate and roadstone (coated and uncoated, including high PSV roadstone), as well as building stone. The process plants have crushing circuits with up to four stages with primary jaw crushers, secondary cone crushers and cone or impact crushers in subsequent stages. Production of quarry fines is up to 35% of throughput and is utilised wherever possible in asphalt, concrete blocks, in Bentonite Enhanced Soil and as inert fill material.

Limestone quarries: Limestone quarries mainly produce crushed rock aggregate and roadstone (coated and uncoated), as well as agricultural lime, armourstone, concrete blocks, ready mixed concrete, lime and mineral filler. The process plants have crushing circuits with up to four stages with primary jaw, gyratory or HSI crushers, and HSI crushers, cone crushers, or hammer mills in the subsequent stages. Limestone quarries typically produce 14 to 20% quarry fines; this is mainly used in concrete block manufacture and asphalt, or Type 1 sub-base.

Igneous and metamorphic rock quarries: Igneous and metamorphic rock quarries mainly produce crushed rock aggregate and roadstone (coated and uncoated), as well as railway ballast, armourstone, ready mixed concrete, gabion basket and drainage stone, and Type 1 sub-base. The process plants have crushing circuits with up to five stages with primary gyratory crushers or jaw crushers, secondary cone crushers or jaw crushers, and cone crushers or VSI crushers in the later stages. They typically produce 25 to 35% quarry fines. The quarry fines are used in concrete products or washed for use as building or concrete sand.

MINIMISATION OF QUARRY FINES

In the last five years the market for aggregates in the UK has changed. The Landfill Tax and Aggregates Levy have encouraged the use of recycled and secondary material and reduced the use of quarry fines and waste in lower value construction applications. However, quarry fines and waste continue to be produced at the same level as before and stockpiles of these sub-economic materials are increasing at some locations. Consequently, there is a growing need to minimise the production of quarry fines and wastes. Business-related drivers include the need to comply with the planning process (BGS, 2007) and regulation, the need to maximise revenue in the form of saleable products and the need to avoid resource sterilisation within the quarry boundary due to excessive fines stockpiling. Other drivers include the environmental and social consequences of managing quarry fines and waste and the costs of complying with UK legislative regulations.

Process optimisation

The amount of quarry fines produced can be minimised by process optimisation; this typically starts with an audit of the production process, including throughput tonnages, crusher and screen settings, and product gradings. Flowsheet analysis is aided by the use of proprietary computer software such as AggFlow 2006 (aggflow.com) and JKSimMet (www.jktech.com.au) or equipment manufacturers software (such as Bruno as used by Metso Minerals). The behaviour of the crushers can be modelled using theoretical, laboratory or process plant data. Adjustments made to the settings or by changing the type of equipment may optimise the process to give maximum aggregate production and minimise fines production. A case study, using the process optimisation software Bruno, is summarised below:

Sandstone Case Study: This sandstone quarry is located in southwest England and it produces high polished stone value (PSV) roadstone and horticultural sand. This case study represents a simulated process change. The original process plant has a four stage crushing circuit with a primary jaw crusher and cone crushers in the secondary, tertiary and quaternary stages (Figure 1). Production of quarry fines is 55 tph. The existing circuit was modelled using Bruno software and it was found that the model produced a sensible mass balance and equipment loadings. The aim of the simulated process change was to increase the production of saleable aggregate and reduce quarry fines production. The simulated process change involved replacing the tertiary and quaternary cone crushers with a single tertiary vertical shaft impact (VSI) crusher (Figure 2). This was predicted to reduce quarry fines production to 39 tph (a 29% reduction) and would enable a 18% increase in the production of saleable aggregate.

Crushing plant technology

The most common types of crushing technology used are compression crushers and impact crushers. Many crushers incorporate a component of abrasion and attrition, which leads to the production of fine material. 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 more cubical shape but typically also produces more fine particles. Table 4 summarises the key good practice for minimisation of quarry fines in aggregate production plants.

*Jaw crusher good practice***:** Jaw crushers are mainly used in primary crushing to prepare rock for subsequent processing stages and are rarely used as secondary crushers. They do not produce large amounts of quarry fines; 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, less than 1%. Attempts to minimise fines production at the primary stage have little effect as most fines are produced in later stages.

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. A reduction in fines could be achieved by 'trickle feeding' material into the jaw crusher; however this would have an adverse effect on particle shape and also reduce the 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. Many are not fed to their design capacity because the subsequent processing plant does not have sufficient capacity to handle the volume of material that would be produced.

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 (F_{80}; the size at which 80% is finer than the top size of the feed) and the particle-size of the product (P_{80}; the size at which 80% is finer than the top size of the crushed product). The finer the CSS the greater the proportion of fines produced. The CSS is constrained by the need to maintain the nip angle between plates to within 19 – 23^{o}; larger angles cause 'boiling' in the crushing chamber (where the plates cannot grip the rock and it slips up and down). Increasing the CSS in an attempt to reduce fines production may have the opposite effect; it would lead to a greater proportion of oversize material, which would need recrushing and this would generate more fines.

Gyratory and cone crusher good practice: Gyratory are mainly used in primary crushing; as for jaw crushers, any attempt to minimise fines production will have little effect as most fines are produced in later stages. Cone crushers are mainly used in secondary and tertiary roles, where fines production is far higher. They are often used in secondary and tertiary roles as an alternative to impact crushers where shape is an important requirement and fines production needs to be minimised.

Uniform distribution of feed material around the cone crusher inlet allows production of a consistent product and consistent operation of the crusher. Choke feeding 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. Pre-screening of the feed to remove the fines, especially in tertiary crushing, 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 CSS 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.

Impact crusher good practice: Impact crushers tend to be used where aggregate shape is a critical requirement; especially for highly specified roadstone and concrete aggregate applications. However, they also have the reputation for producing excessive fines.

It is important to have an even distribution of feed material; this ensures the maximum contact across the width of the rotor. The initial impact is responsible for more than 60% of the crushing action; the remainder is a result of impact with adjustable breaker bars and inter-particle collision. Efficient transfer of energy from the rotor ensures consistent product gradation and power consumption.

Size reduction is directly proportional to the rotor speed (rotor diameter and speed combine to give a tip speed); it controls the amount of fines produced. Slower rotor speeds will reduce crusher wear and produce fewer fines; however it may adversely affect the particle shape of the product. As the impact hammers and breaker bars become worn, the products become coarser; modern crushers have variable drives that can compensate for this by increasing the rotor speed.

Open discharge arrangements in impact crushers rely on retention of the rock within the crushing chamber. Reducing the gap between the hammers and impact curtain increases the particle retention in the chamber. Closed discharge arrangements rely on a series of grids to retain the material within the crushing chamber; these are generally not adjustable. Reducing the size of the grid apertures has the effect of increasing the residence times of material in the crushing chamber. In both cases, increased residence in the crushing chamber has the effect of increasing the size reduction ratio; however it also reduces the throughput capacity and increases the proportion of fines produced.

Table 4. Good practice for quarry fines minimisation

- Crushing should be carried out in several stages with small size reduction ratios; the number of stages should be optimised to limit fines production.
- It is generally accepted that compression crushing (i.e. jaw and cone 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
- Closed side setting of jaw and cone crushers should be set to give a size reduction ratio of less than 6:1.
- Choke feeding is preferable; this helps to reduce impact and wear on the crusher components, improves the throughput capacity, minimises the top size and reduces the proportion of 'flaky' material produced. However, it may also increase the proportion of quarry fines produced; crushing under non-choke conditions (although not ideal for producing 'good' particle shape) will help to minimise fines production.
- Material should be uniformly distributed as it is fed into a crusher to ensure uniform crusher wear and product properties.
- Lowering the crusher speed will reduce the amount of fines produced; however it also reduces crusher throughput and produces poor particle shape.
- Screening and recirculation of oversize material will improve aggregate particle shape; however it will also increase fines production.
- Cone crushers should be considered as an alternative to impact crushers where both good (cubical) particle shape and fines minimisation are required.

FUTURE TECHNOLOGY

Future production trends in 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. The strategic response to climate change will drive the agenda for energy supply and consumption; voluntary and regulated responses to climate change will affect the industries consumption of energy.

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. The energy used to produce a tonne of aggregate is equivalent to approximately 10kg of CO_2. It is likely 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. Currently, assessment tools used to determine CO_2 emissions assume that roughly 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.

Modern crushers have been designed with a good understanding of feed characteristics, machine geometry, crushing chamber, the relationship between power draw and crushing force, speed of operation and lubrication/ hydraulic system conditions (Trueman, 2001). Future developments of crushing technology will be driven by the industry focus on:

- higher productivity at reduced costs per tonne
- 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 integrated into automated systems. These ensure that the crusher always operates within ideal parameters, promoting constant choke-feeding required for good particle 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.

DISCUSSION & CONCLUSIONS

The key benefits of quarry fines minimisation include a reduction in waste production, an increase in mineral resource use efficiency and an increase in the production of saleable aggregate. The need for quarry fines minimisation was reinforced by the introduction of the Aggregates Levy in 2002, which aimed to address the environmental costs associated with quarrying operations by reducing the demand for primary aggregate and encouraging the use of alternative materials. An increase in the Aggregates Levy, which rises from £1.60 to £1.95 per tonne in 2008, will strengthen the need to minimise fines production.

Quarrying operations should regularly conduct process optimisation audits to ensure that they produce the lowest achievable proportion of quarry fines. Ongoing process optimisation is also important including: maintaining closed side settings and choke feeding conditions in compression crushers, using reduction ratios of 6:1 or lower, maintaining uniform feeding conditions for impact crushers and monitoring the condition of crusher wear parts. Where particle shape is important, quarrying operations should consider replacing vertical shaft impact crushers with cone crushers; this is likely to reduce fines production by up to 50%.

As a last point, in answer to the question posed in this paper; we cannot produce 10mm aggregate without fines. However, we can minimise fines production; the processes summarised in this paper outline how this can be done. Inevitably, over time the products demanded by society will require raw materials with higher quality. Aggregates will be no exception and it is up to the quarrying industry to demonstrate that it can devise the technology to minimise fines production and optimise resource utilisation.

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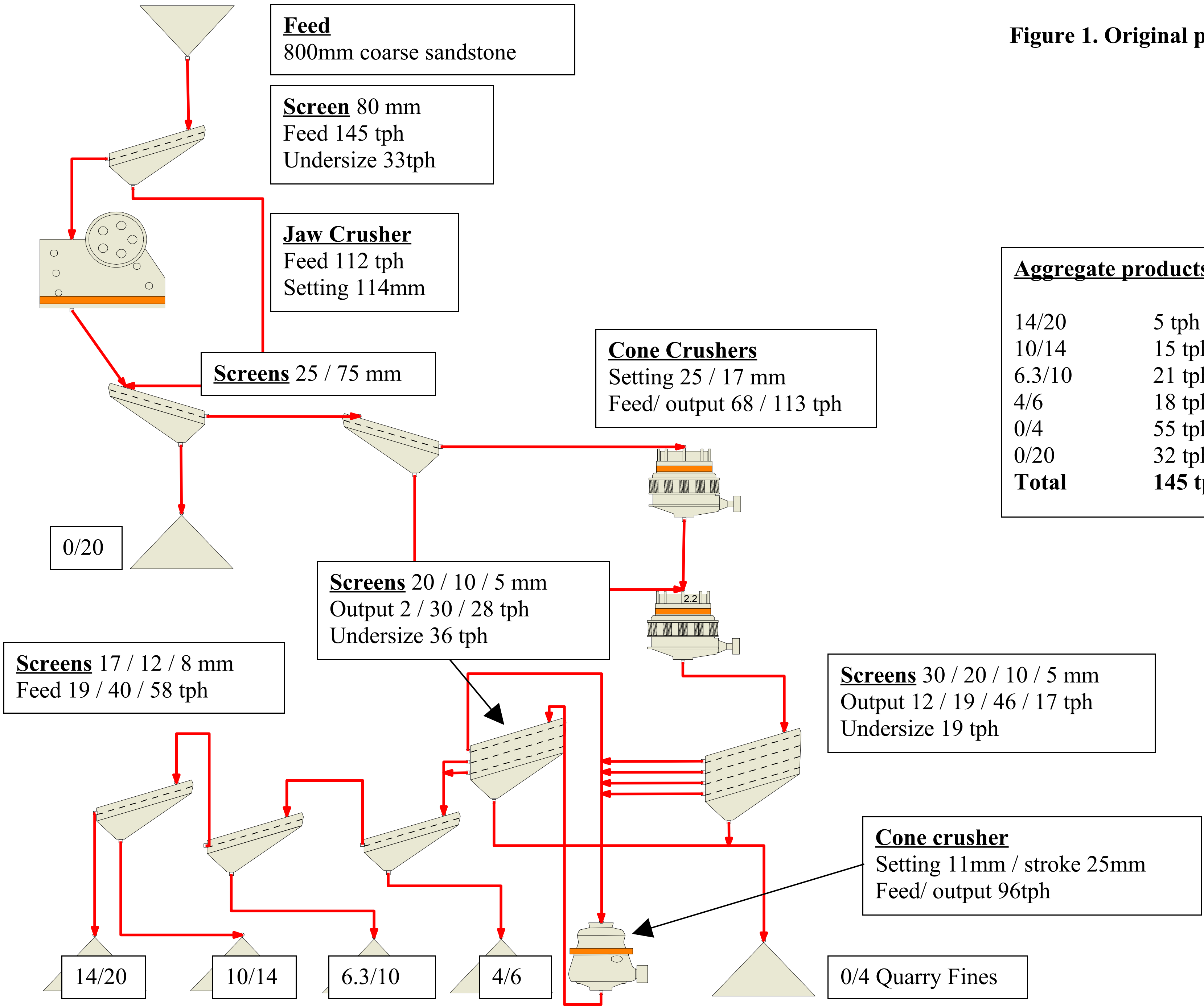
Figure 1. Original process flowsheet



Aggregate products

14/20	5 tph	**4%**
10/14	15 tph	**10%**
6.3/10	21 tph	**14%**
4/6	18 tph	**12%**
0/4	55 tph	**38%**
0/20	32 tph	**22%**
Total	**145 tph**	**100%**

Figure 2. Modified process flowsheet