Report

Mobile processing and use of short-transported construction aggregates, challenges and opportunities

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Preface

This report has been written within the project “Local use of rock materials” (Kortreist stein). “Local use of rock materials” is an IPN-project in a program by the Research Council of Norways for User-driven Research based Innovation (BIA). Veidekke Entreprenør AS is the owner of the project.

The main objective of the project, is to develop new technological solutions and tools, smart business models and good regulation processes. This, to be able to utilize rock materials from infrastructure projects and local quarries in a superior and sustainable manner. Superior utilization means both use of local materials in unbound road- and railway construction as well as aggregates in asphalt and concrete.

The project aims towards energy effective materials production and optimized utilization of non-renewable rock resources. The project will facilitate and establish technologies to increase value for money with local materials. The innovation in the project is directed towards laws and regulations that control the utilization of local materials and methods of assessment for utilization of rock materials mainly from tunneling. In addition, an approach to methods for practical implementation of use of local materials will be covered.

A consortium of the following partners from industry, public administration and research institutes are currently working on these four main topics:

- Laws, regulations and resource planning
- Contracts, business models and incentives
- Production and utilization
- Sustainability and energy efficiency

“Local use of rock materials” has a 17 million budget (NOK) and a duration of three years (from 2016). It is financed through the Research Council of Norway (40%) and the industrial partners (60%).

The publications from "Local use of rock materials" have been prepared by professionals at the partners in the project. Every effort has been made to ensure that the content is in accordance with the common knowledge at the time the project was completed. However, errors or omissions may occur.

The authors and the project management have no responsibility for errors or omissions in publications and possible consequences.

It is assumed that the publication is used by competent and knowledgeable persons with an understanding of the limitations and assumptions that are used.

Eivind Heimdal	Torun Rise
Project owner	Project manager

Summary in English

Aggregates are major constituents in construction, the global request for which approaches some 22 billion tonnes per year. Some major challenges follow; first of all the dependency on geological conditions and the availability of resources; secondly the traffic, emissions and energy use connected with transportation; thirdly the technology of utilising resources with a variety of properties to meet user requirements; and finally – getting more awareness – the land use conflicts and environmental impact of the aggregate and quarrying industry, and the need for making these activities sustainable. Geological resources are non-renewable, which e.g. can be seen in the rapid depletion of natural sand/gravel deposits. This causes increasing awareness along with environmental impact; conflicts of interest concerning land-use; sustainability in mass balance; and not least – increasing transport distances required to get the materials to the places of use. The principle of a Best Available Concept (BAC) for aggregate production and use was introduced by Danielsen and Kuznetsova [1], working with four essential phases: Inventory and planning, Quarrying and production, Use of aggregates, and Reclamation of mined-out areas. Important in such a concept is the use of novel LCC and LCA tools to enable the calculation of environmental and economic consequences of decisions. The development of concepts and technologies to utilise local aggregates on a short-travel basis, is an important part of this. The aim of such a development is to obtain production processes on mobile platforms to offer on-the-run solutions that can greatly reduce the need for transport to and from site, make more tolerant user techniques of excavated or secondary rock materials, and not least, contribute to a significant improvement of mass balance.

Sammendrag på norsk

Tilslagsmaterialer er essenstelt for all bygg- og anleggsvirksomhet. Verden forbruker mer enn 22 milliarder tonn hvert år av sand, grus og pukk. Dette reiser noen utfordringer. En første utfordring er knyttet til tilgangen på mineralressurser med egnete egenskaper. Et annet viktig forhold er knyttet til trafikk, utslipp og energiforbruk tilknyttet transport, og en tredje utfordring er teknologien som skal til for å utnytte ressurser med ulike iboende egenskaper som skal møte ulike brukerkrav. Sist, men ikke minst, og som får stadig større oppmerksomhet, er utfordringen knyttet til båndlegging av store uttaksarealer, med arealbruks- og interessekonflikter og miljøpåvirkninger som tilslags- og steinbruddvirksomhet gir, og behovet som ligger i å gjøre denne virksomheten enda mer bærekraftig. Geologiske ressurser er ikke-fornybare, noe som tydeliggjøres i meget stor grad for våre sand- og grusressurser. Norske sand og grus-forekomster er i ferd med å tømmes. Slike forhold, sammen med miljøpåkjenninger, fører til økt samfunnsoppmerksomhet, interessekonflikter med hensyn til arealbruk, økte transportavstander som nødvendiggjøres for å få tilgang til tilslag der de trengs. Hovedstikkord for å møte disse utfordringene er bærekraftig massebalanse. Prinsippet med Beste Praksis Konsept (Best Available Concept, BAC) for tilslagsproduksjon og -anvendelse ble introdusert av Danielsen og Kuznetsova [1], og fokuserer på gevinsten som ligger i å arbeide med fire, vesentlige faser: Forarbeider og planlegging, Uttak og prosessering, Tilslagsanvendelse og Tilbakeføring av uttaksområdet. Viktige verktøy i et slik konsept er Livssyklus- og livskostnads-analyser (LCA og LCC) som kan beregne miljø- og kostandskonsekvenser av løsningsalternativer. Utvikling av konsepter og teknologier for å utnytte lokale tilslagsressurser på en kortreist måte, er en viktig del av dette. Målet med en slik utvikling er å realisere produksjonsprosesser på mobile knuseplattformer for å tilby fleksible anleggsløsninger som kan redusere transportbehovet til og fra anvendelsessted, fremskaffe mer brukervennlige anvendelsesteknikker av uttatte og sekundære bergmasser og ikke minst, bidra til en betydelig forbedring av massebalansen.

1 Introduction

The present report will discuss the need for a holistic approach to quarrying and use of short-transported mineral aggregates including technological, economic and environmental consequences of using local and/or secondary rock materials. This issue and need for research by far emerges from the considerable research work done in the aggregate part of the CRI COIN https://www.sintef.no/en/projects/coin/coinp/#/. Some discussions in the present report are taken from the authors´ participation in COIN [2].

1.1 Overall objective

In the future, society cannot afford to deposit or dump a considerable part of the mineral resources we extract from the nature, either as blasted rock from excavation or tunnel work; or as quarry waste from hard rock or dimension stone quarries. We can especially not justify doing so at the same time as we transport the same sorts of materials from far-away sources. Today this is due to strict quality requirements at the place of use, or lack of technology in meeting these requirements using the locally available rock materials. Inferior technology when it comes to effective processing to avoid e.g. surplus fines and to obtain a mass balance of all sizes produced is also an important element in such short-coming. Industry actors as well as our politicians and lawmakers will increasingly have to adapt to priorities regarding environmental impact and sustainability. This is a primary background for and objective of the short-transport aggregate project [3].

1.2 Background – mobile aggregate production plants

Utilising of short-transport aggregates will depend on an efficient and high quality use of mobile production equipment. This applies to crushers as well as sorting equipment (sieves/screens, washing plants) – and the combination of them. A significant part of the report is dedicated to this theme, and especially to the recent development in mobile process equipment and the opportunities to set up production concepts drawing on these developments.

There is a two-fold motivation for this development: One is the need to reduce un-necessary transport work of aggregates from far-away sources. This is due to economic as well as environmental aspects.

The second area of motivation is connected with the locations for aggregate use, first of all when it comes to road construction: Road construction projects year 2015 in Norway consumed 50% of the total production of aggregates. From that amount unbound aggregates represent approx. 73% of the volume [4]. In comparison to a typical concrete or asphalt production where usually production plants are static and fixed to certain location, unbound aggregates are placed directly after production into the road structure. This encourages the use of mobile aggregate production plants using the upcoming suitable rock material resources as a raw material to minimize the transportation needed. In addition the work done on loosening the solid rock is utilised and handling of that material is reduced to a large degree.

1.3 The holistic approach

It is also vital that the entire materials logistics is taken care of. There will be a challenge in considering and documenting the functional characteristics of the aggregates, since these will be more variable and less predictable due to geological variations along e.g. a tunnel line, than what will normally be the case in an ordinary quarry. This also calls for a more tolerant materials design, which often may collide with strict normative requirements. The use of resources should to a greater extent be a bottom-up issue – letting the availability of resources be the starting-point, ruling which technical and architectural solutions to be selected. Today, however, we mostly see a top-down prioritising, where the search for suitable resources is the final step in the project planning, after concepts and design have been selected.

This also has to do with the environmental challenges of the activities, e.g. connected with road construction: Road construction is by nature a wide geographical project, spread over a long distance. If the construction materials are produced on one fixed spot, the average transportation distance to site is long. The primary method of transportation will in most cases be trucking, which will be responsible for considerable social and environmental loads; safety risks from the traffic, dust emissions, noise and a general energy in-efficiency. And not least; long transportation distances add significant costs to a project. Also, of course, an aggregate production plant will cause environmental challenges during rock processing and aggregate handling and stockpiling. But this will normally be more concentrated in space and time.

1.4 Availability of resources

Mineral resources is the most used commodity in the world, second only to water. Aggregates (sand, gravel, crushed rock) are a prerequisite for all building activities – roads, airports, railways, harbours, and buildings. More than 70 % of concrete and 90 % of road materials are made up of aggregates. Approximately 10 tons per capita is the annual consumption in Norway and many other industrialised countries, and the total world market for aggregates approaches 22 billion tons per year [1].

Mineral aggregates can only be excavated where nature has placed them, but they have to be used where society needs them. More and more often that is not at the same place. This entails transport, and we also see an increasing tendency of "*Not in my backyard*" attitude among politicians, actualizing the challenges of future access to resources.

Traditionally most parts of Norway have been well served by sand and gravel of acceptable quality. However, the post-war decades have seen an extensive downsizing of these resources; it has been estimated that close to 80 % of all sand and gravel taken from the nature during all times, has been taken out in our generation. So, several of the major deposits are already, or about to be, emptied, or the remaining part of them is prioritised for other purpose.

But our country is still rich in hard rock, rock types with a variety of technical properties. Most places suitable rocks for all relevant purposes can be found within acceptable distances, at least if not specifically strict requirements are applied. Norway is today one of the European countries with the highest percentage of crushed hard rock in the aggregate production. And it is also one of the primary exporters of such materials within Europe [1].

Crushed hard rock for coarse aggregates have been made and used for decades, and the quarrying and production of such materials are well-proven technology. The challenge has been to be able to utilise the so-called fine sizes (below 2 or 4 mm) in an economic and technically satisfactory manner. Approximately 30 % of the rock materials after a crushing process will normally be within this size range, and quarries world-wide have been almost drowning in surplus fines [2] [5] [6].

Research and technical development during some decades now have brought about promising new technology for both the processing and use of these aggregate sizes, making them fully competitive with natural sand. Still, however there is a challenge regarding mass balance and in extending this technology from the large, well equipped fixed plants and quarries to the smaller ones, and especially to mobile plants.

2 Sustainability and environmental challenges

In 1989, the Brundtland Commission articulated what has now become a widely-accepted definition of sustainability: *"[to meet] the needs of the present without compromising the ability of future generations to meet their own needs".*

However, as pointed out by Danielsen & Ørbog [5] aggregate production is, by the strictest definition, non-sustainable, since aggregate resources are non-renewable. However, the term sustainability used in this context, can be used to characterise an aggregate production, which is in an optimum balance with the geological resources used, as well as with the various kinds of physical and societal surroundings. Any exploitation of natural resources should give a maximum of added value to the society, without causing a need for re-deposition or pollution.

Sustainability in the aggregate and concrete industry was one of the issues that were focused in the European network project ECO-serve (2002-2006). The Aggregate and Concrete Cluster (Cluster 3) of the project produced reports of the European situation regarding aggregate supply and research challenges, as well on the current Best Practice in the industry with reference to environmental requirements and sustainability. A "BAC" (Best Available Concept) was suggested taking into account in the environmental and sustainability aspects along the entire process line from materials inventory, via production and use, to final area reclamation [6].

Danielsen [7] presented an overview of the ECO-serve project in an article discussing the sustainability in the production and use of concrete aggregates. Aggregates are important construction materials, both for new constructions and maintenance. Aggregates are a valuable natural resource and it is our obligation to use it sensibly, in particular in highly populated areas where the demand is great and costs may increase due to long transportation distances. Good understanding of the basic material properties, usage possibilities and quality is significant for sensible use. It is further important for authorities to be up to date with locations and details of existing and potential quarries.

The aggregate industry is presently facing a growing, public awareness relating to the environmental profile of their activities. Important areas of concern are:

- The non-renewable character of the geological resources, especially in regions facing a coming shortage of adequate local materials,
- The environmental impact on neighborhood and society (noise, pollution, effect on bio diversity) of the quarrying and of the materials transport related to the quarrying activities,
- Land use conflicts between quarrying and e.g. agriculture, recreation, building sites, archaeology - especially in densely populated regions,
- A lack of sustainability in production, characterized by inferior mass balance (i.e. high percentages of e.g. surplus fines to be deposited) and a high-energy consumption needed pr. ton aggregate produced,
- The potential environmental or health impact of the very materials produced, due to e.g. leaching of heavy metals, radioactivity, and to special minerals suspected to have hazardous health properties.

These questions in the relation between the aggregate industry and its surrounding society, will by far be determinant for the industry's survival potential: In the future, only those companies and branches will survive who can earn their public acceptance from an active use of environmental parameters in their planning and execution of own activities.

The real challenge will be to merge the environmental issues with the industrial ones; to create aggregate production plants, which are at the same time environmentally friendly and economically profitable, which integrate quarrying and industrial production, and finally – for which there exist plans for restoration and area use after completed quarrying period.

Knowledge and possibility to analyze easily the material properties is a key thing in the selection of aggregate use to ensure optimum use of the resource. For instance, high quality (and valuable) aggregate may be used for the high-quality need applications like concrete and asphalt layers whereas aggregates with lower quality may be selected for massive fills, base and subbase road layers where quality demand is not as strict. Unnecessary damages to the nature may be prevented; optimum exploitation of the resource may be achieved. Environmental effects may be better estimated. All these are important goals on the way towards sustainable development.

2.1 Energy and environmental impact

In a report by Lagerblad et al. [8], it is pointed out that the crushing of aggregates requires energy implicating influence upon the environment. It is also claimed that the transport of aggregates is more than 20% of all heavy truck transportation, and at transport distances longer than 50-100 km, the cost of the transport is more than the price of the aggregate itself.

Some figures regarding energy consumption and corresponding CO_2 emission of aggregate production and transport has been compiled for a Norwegian aggregate producer [9]. The figures are based upon some average experience data and some best guesses.

As a measurement of energy, the figures of emission of CO_2 per ton of aggregate, has been used. This approach excludes the cost of energy from electrical power, which is commonly used in aggregate production in Norway. However, if electrical power comes from coal power plants, a figure of 0.28 kg CO_2 emission per kWh may be applied.

Table 1 presents figures to produce crushed aggregate originating from blasted rock.

Table 1: Energy consumption – Crushed gravel production, from blasted rock.

Activity	Energy sources	Consumption		CO_2 pr unit		Emission CO_2 (kg CO_2/ton)
Blasting	Explosives	0.25	kg/t	2.66	kg/kg aggregate	0.67
Production	Diesel oil	0.57	liter/t	2.69	kg/litre diesel oil	1.53
Production	Electrical power	2.30	kWh/t	0	kg/kwh	0
					Total	**2.20**

Table 2 presents figures for the energy consumption of transportation. Based upon these figures it can be calculated that e.g. local transport of aggregates by a lorry, at 17.7 km, equals the CO_2 emission per ton of aggregate as to produce crushed gravel from blasted rock.

Domestic transportation of aggregates by a 1.000-ton vessel, e.g. 40 km, implicates 0.6 kg CO_2 emission per ton of aggregate. In the case of export of aggregates, e.g. of distances 600 km, the CO_2 emission per ton of aggregate for a 4.000-ton vessel is 10.7 while for a bigger vessel (27.000 tons) the emission is only 3.9.

Table 2: Energy consumption – Transportation.

Type of transport	Energy source	Consumption (litre/km)	Ton pr unit	Consumption (litre/ton x km)	Emission CO_2 (ton/km)
Lorry	Diesel oil	0.6	13	0.0462	0.1242
Vessel, domestic	Diesel oil	5.7	1.000	0.0057	0.0153
Vessel, Export 1	Heavy oil	26.4	4.000	0.0066	0.0178
Vessel, export 2	Heavy oil	64.4	27.000	0.0024	0.0064

CO_2 pr unit: 2.69 kg/litre diesel

3 Aggregate technology

The term “Aggregate technology” may be applied for a combined use and interaction of the three essential fields of knowledge necessary in order to exploit, manufacture and use a mineral aggregate for a construction purpose [10]:

- **Geology** – the geological basis for the materials
- **Production technology** – the various equipment and methods available to transform the geological material into a well-processed building material.
- **Materials technology** – the proportioning and use of the product material in order to meet the over-all requirements.

The characteristics of the geological material, mineral composition, structure and texture, crystal size, alterations, and for a sand/gravel; the particle shape, grading and surface properties – will be determinant both for product materials properties and for the choice of manufacturing processes.

There is interdependency between geology and production technology, as one and the same manufacturing process will not be suitable independently of the rock type and the quarry setting. Similarly, an optimum e.g. concrete proportioning will have to be adapted to the aggregate characteristics, given partly by the geological parameters, partly by the parameters determined from processing. And finally – the other way around – the requirements to the end product will often be decisive for the choice of the geological raw material as well as for the production process to be designed.

These interactions are illustrated in Figure 1 below.

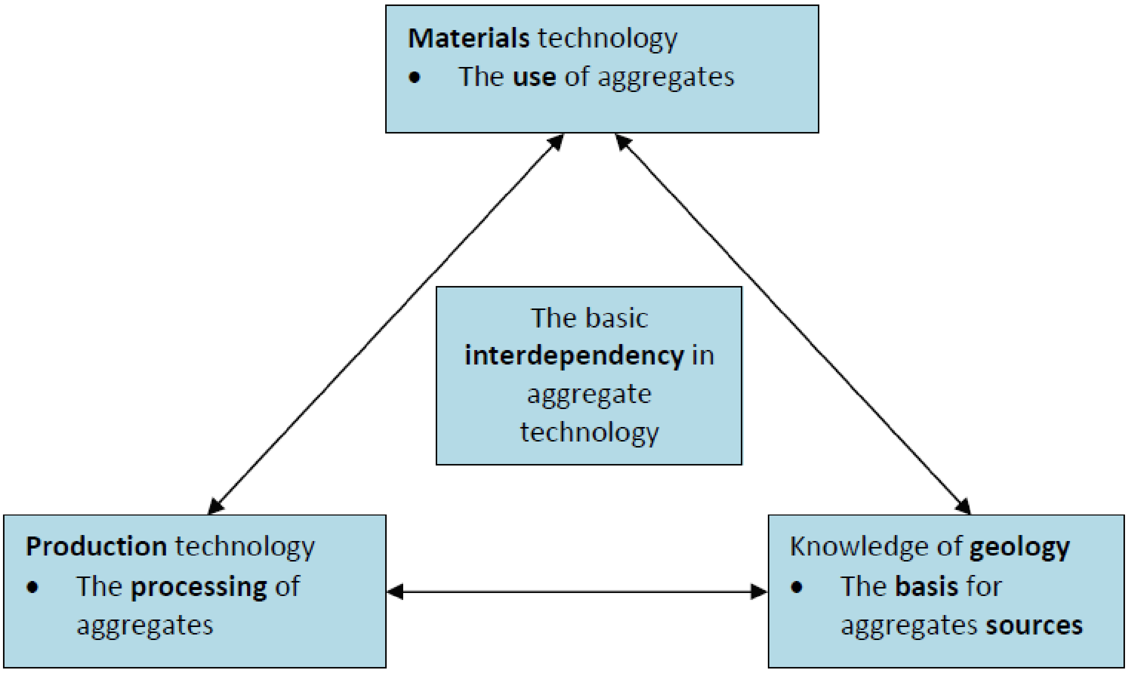

Figure 1: Principles of aggregate technology [10].

3.1 Technical challenges

Mobile crushing plants, track or wheel mounted equipment, are easily transportable units. Depending on type of equipment, the crushing plant can start operation after 2 to 8 hours since arriving to quarry. The first technical challenge in mobile crushing plants has been the consistency of aggregate product quality. Lack of surge bins and stockpiles can cause variable load on crushers and screens resulting in severe quality variances. Also, there can be limited possibilities for setting an optimal crushing plant flowsheet with mobile equipment to enable highest quality aggregate production. The second technical challenge is the rock material that applies especially in utilizing rock material in tunnel projects. It is quite difficult to estimate what comes ahead and rock quality can be greatly variable.

However, the majority of the aggregate masses in a new road-building project consists of base and subbase materials. To give an idea, a road is a two-meter-deep structure containing 1.8 m layer of base materials without high quality demands and 0.2 m top layer with high quality aggregate. Top layer calls for high quality aggregates to ensure layer durability and comfort and safety for the vehicles running on it.

Keeping in mind the fact above, big masses of road structure are easier to produce with in situ mobile production plants. However, controlled production methods are needed to meet the needed specification set for base and sub base layer materials. Anyhow, base materials are meant to last very long without maintenance. Wearing surface is instead relatively easy to maintain and to renew after it has lost its properties.

3.2 Economic challenges and options

As pointed out in a forecast presented by Vulcan Materials Company [11], as demand increases and supply decreases in high-growth areas, new approaches to supplying aggregates will be required, and aggregates will travel greater distances from point of production to point of consumption. This will likely result in cost increases for aggregates and aggregates-related construction materials such as hot-mix asphalt and ready-mixed concrete. It will also increase the environmental impact in terms of pollution and energy consumption.

O´Flynn [12] points out that the major cost component of aggregates as a bulk low value commodity, is transport, and the aggregates must be won as close as possible to the urban centers where they are consumed. Generally, aggregate must be won as close to consumption point as possible. In the case of a road project, aggregate should be produced from the materials available on-the -way; rock cuttings, tunnels blasted or from local quarrying close to consumption. A change to alternative materials sources will then also necessitate the utilization of the state-of-the-art mobile crushing technologies.

Economically, mobile quarrying concepts result into a win-win situation. Reduced transport costs together with reduced production and raw material costs associated with mobile quarrying not only means avoiding landfilling big masses of valuable rock material, but also makes the operation economically very profitable.

4 Mobile crushing and screening plants

4.1 Geological issues

As shown in the Figure 1, there is a key interaction between the prevailing geological conditions, the user properties of aggregates and the challenges and opportunities connected with processing technology. At the end of the day, it is the geological conditions that set the limits for aggregate performance and also defines how far a processing plant can improve the rock materials. Therefore, a thorough knowledge and understanding of the local geology is vital. Table 3 gives a simplified overview of rock types and expected aggregate properties in different geological areas in Norway.

This can be a special challenge for road projects and even more for tunnels, where the location will be determined by the road or tunnel alignment, with almost zero freedom in choosing where to excavate. This calls for detailed geological investigations in order to decide whether or how the excavated rock can be taken out, processed and used. Especially for tunnels such pre-investigations will normally be very challenging, and problems e.g. connected with deleterious and unsuited rocks and minerals can occur in the middle of a project. This is what happened in connection with the Follobanen project, where out-of-standards content of pyrrhotite was detected in the rock materials taken out from the tunnel [13].

Mobile processing can also be economically successful in utilising quarry waste (QW) from fixed hard rock quarries. Several dimension stone quarries have a considerable QW percentage, and a geological investigation can often decide whether and how this QW can be re-processed as an aggregate, and for which user purpose. A recent example is the schist quarries at Oppdal. With a QW-% of more than 80, this quarry would become choked by its own surplus rock within a few years. However, two factors made it possible to make a good, marketable aggregate out of this surplus by using a well-designed mobile plant: First, the rock was shown to have excellent mechanical properties for use in the nearby market, including road projects. Secondly, the spacing between the mica layers (which makes the rock schistous) was suitable for making well cubical aggregates at marketable grain size for big parts of the surplus [14].

Table 3: Geological regions and simplified aggregate properties.

<table>
<tr><th>Geological area</th><th>Period</th><th>Predominant rock types</th><th>Properties for roads</th><th>Properties for concrete</th></tr>
<tr><td>Oslo area</td><td>Permian to Carboniferous</td><td>Basalts, syenites, porphyries, diabases</td><td>These rocks normally have good mechanical properties</td><td>Check aggregates for potential AAR</td></tr>
<tr><td>Sediment basins in the mountain range</td><td>Silurian to Devonian</td><td>Sandstones and conglomerates</td><td>A small location of rocks with good mechanical properties</td><td>Check aggregates for potential AAR</td></tr>
<tr><td>Overthrust areas, Northern Norway</td><td>Precambrian to Silurian</td><td>Schists, marble, plutonic rocks</td><td rowspan="2">Big variations. Locally both greenstones, trondhjemite, rhyolite and quartz schist may produce good aggregates, but the large areas of mechanically weak schists are not suitable</td><td rowspan="2">As for road materials, but rhyolites should be checked for potential AAR</td></tr>
<tr><td>Overthrust areas, Trøndelag and north</td><td>Cambrian to Silurian</td><td>Schists, sandstone, greenstone, trondhjemite, gabbro</td></tr>
<tr><td rowspan="3">Overthrust areas in the mountain range</td><td rowspan="3">Precambrian</td><td>Gneisses</td><td>The gneiss areas in the mountain range normally produce good aggregates</td><td>Normally well suited, but some locations have shown AAR</td></tr>
<tr><td>Sandstone, schist, plutonic rocks</td><td colspan="2">Big variations. Local bedrock and aggregates should be analysed and tested</td></tr>
<tr><td>Sandstone, schists</td><td colspan="2">These areas may be challenging to mechanical properties as well as to durability (AAR and physical weathering)</td></tr>
<tr><td>Overthrust along the mountain range margins and in the Oslo area</td><td>Cambrian to Silurian</td><td>Schists of clay and calcite, hornfels, alum-schist in the Oslo area, mica schists along the mountain range</td><td colspan="2">Very challenging areas regarding any use of construction aggregates. The Oslo area contains all from the very hard hornfels to the reactive alum-schists, via weak schists and slates</td></tr>
<tr><td>Sediments e.g. in Finnmark</td><td>Precambrian to Silurian</td><td>Sandstone, schist, limestone</td><td colspan="2">Variations in rock type and properties, thorough investigations recommended in each case</td></tr>
<tr><td>Overthrust, basement</td><td>Precambrian, but influenced by the Caledonian orogenesis</td><td rowspan="2">Metamorphosed sediments, volcanic rocks, gneisses, granites, anorthosite and similar</td><td colspan="2" rowspan="2">Generally aggregates of good quality for most purposes. AAR is quite rare, and mechanical properties are good. These are areas with an extensive aggregate industry, and where quality documentation will be available.</td></tr>
<tr><td>Basement</td><td>Precambrian</td></tr>
</table>

4.2 Extracting and blasting

The blasting of rocks is regarded as the first stage in the production of aggregates. In the case of utilizing in-situ rock materials, drilling and blasting parameters cannot always be selected optimally for the crushing and screening plant. In a tunneling project rock is usually blasted to a finer size comparing to a need in a crushing plant. On the other hand, it can happen that blast intensity must be reduced close to buildings resulting into much coarser shot rock. Also in a fixed quarry, rock properties and details can be found and learned resulting into close to perfect drilling and blasting parameters.

It is known that drilling and blasting operation affects the ROM result (ROM = run of mine material, also called Quarry run). According to Nielsen [15] the blasting operation will strongly influence the generation of fines after both blasting and crushing. Drill hole deviation together with the drill hole diameter, powder factor and velocity of detonation are the most important blasting parameters with respect to the generation of fines.

Most of the fines generated by blasting originate from a volume around each drill hole. Hole deviation will cause an increased amount of fines where two drill holes are too close to each other. It may also be possible that the amount of fines will increase in high confinement areas due to high levels of strain energy being accumulated in the rock before it finally breaks.

Bohloli [16] emphasizes that the rock mass properties are of great importance concerning blasting and subsequent crushing performance, where these properties are of great importance to the design of blasting. The use of standard blasting designs without regarding such characters, will lead to over-blasting, in most cases, or under-blasting in other ones. Fines generation and damage to adjacent rock are common problems in the case of over blasting. On the other hand generation of large blocks is one of the under-blasting consequences. Using the right type and right amount of the explosive material will considerably decrease the cost of blasting operation and consequence processing. It is further argued by Bohloli that most attention has been paid to the explosive material characteristics and less to the properties of the rock mass [16].

All in all, in case of utilizing short travel aggregates ideology, it is necessary to realize that feed material to mobile crushing plants is not as consistent as in a fixed crushing plant operation. We can now refer to the “aggregate technology” triangle in Figure 1: The characteristics of the geological material – mineral composition, structure and texture, crystal size, alterations, and for a sand/gravel; the particle shape, grading and surface properties – will be determinant both for product materials properties and for the choice of manufacturing processes. The choice of manufacturing process for variable feed material conditions in detail will be discussed in the following chapters.

4.3 Aggregate production flowsheet considerations

The usage of flow sheet and crushers should be considered case by case. Crusher selection is highly influenced by local application requirements and rock material used. Some general guidelines:

- For high capacity and low-quality requirement, cascade design is used. In cascade design, aggregates are sorted out after each crushing stage.
- For high quality products, a selective circuit is used. In this design all final products are coming from the last crushing stage with highest possible quality. In this design also production consistency is taken into account, last crushing stage feed material is controlled and consistent. Last crushing stage feed grading is also optimized against product quality: limited feed top size and including smaller sizes, but no sand, to allow proper interparticle crushing effect. For the production consistency and high production rates, crushing stages are typically separated by feed bins, to ensure proper and controlled crusher feeding. Also process automation is utilized to make process control easy and centralized.
- After primary crusher, a surge stockpile is used to allow production rate variations without interrupting downstream process and to maximize general crushing plant utilization ratio.

See examples below in Figure 2 to Figure 5.

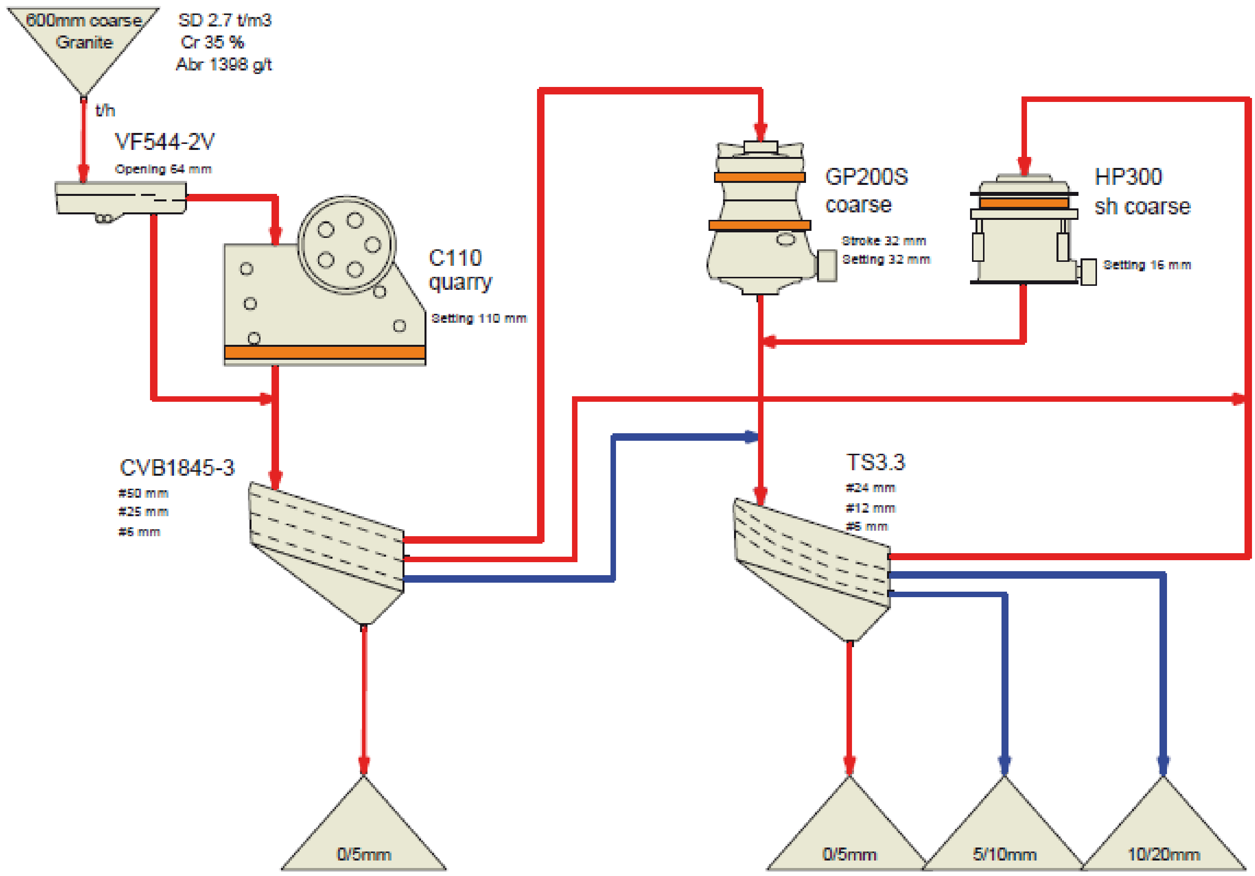

Figure 2: Process example 1: Three stage crushing plant, maximizing the capacity. All –20 mm particles screened directly into products. Capacity 320 tph.

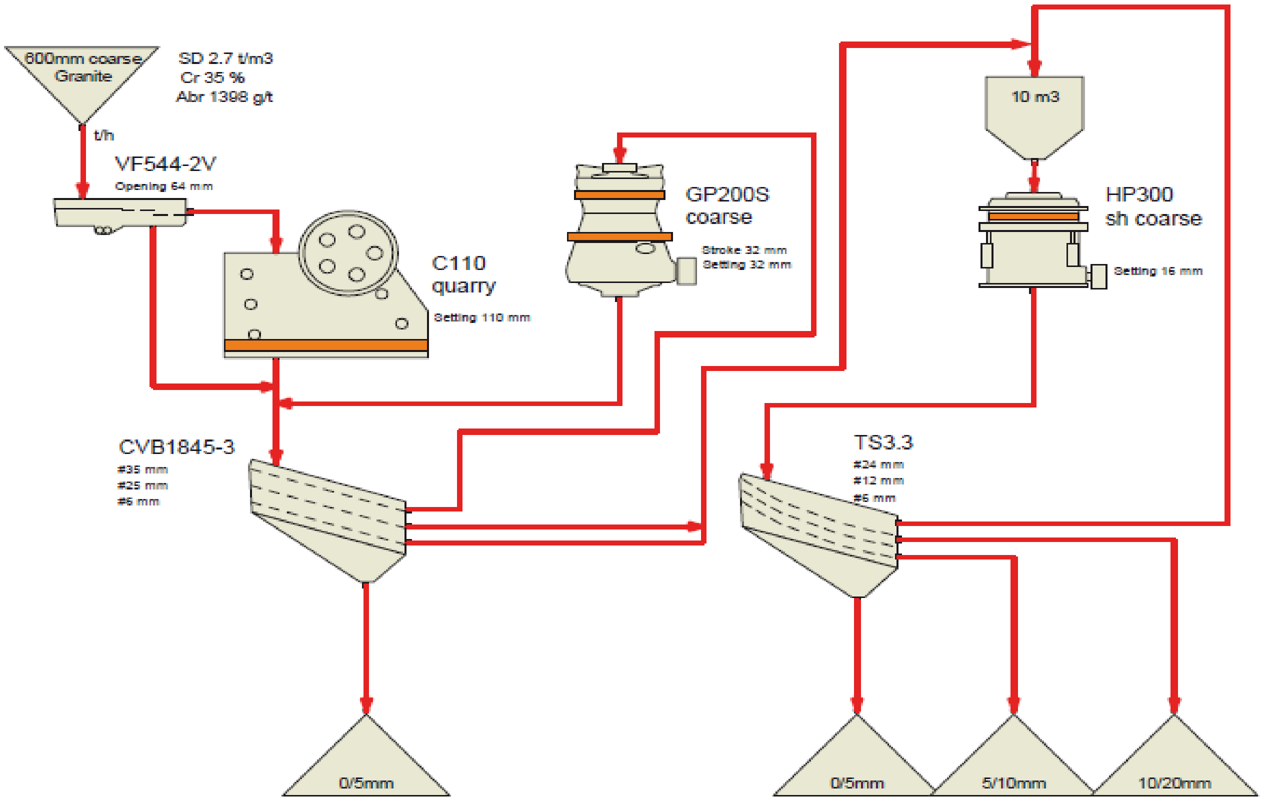

Figure 3: Process example 2: Three stage crushing plant, maximizing the quality. All products are done by tertiary cone. Capacity: 200 tph. Crushing equipment is same as in process example 1.

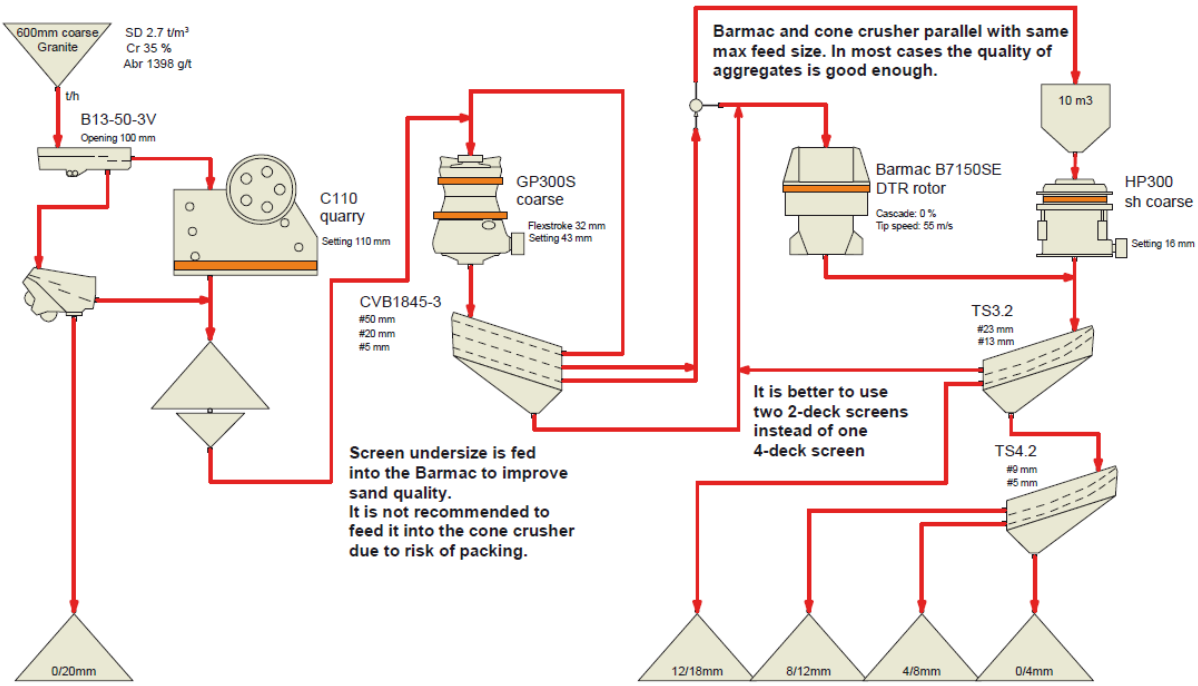

Figure 4: Process example 3: Concrete aggregates – 330 tph.

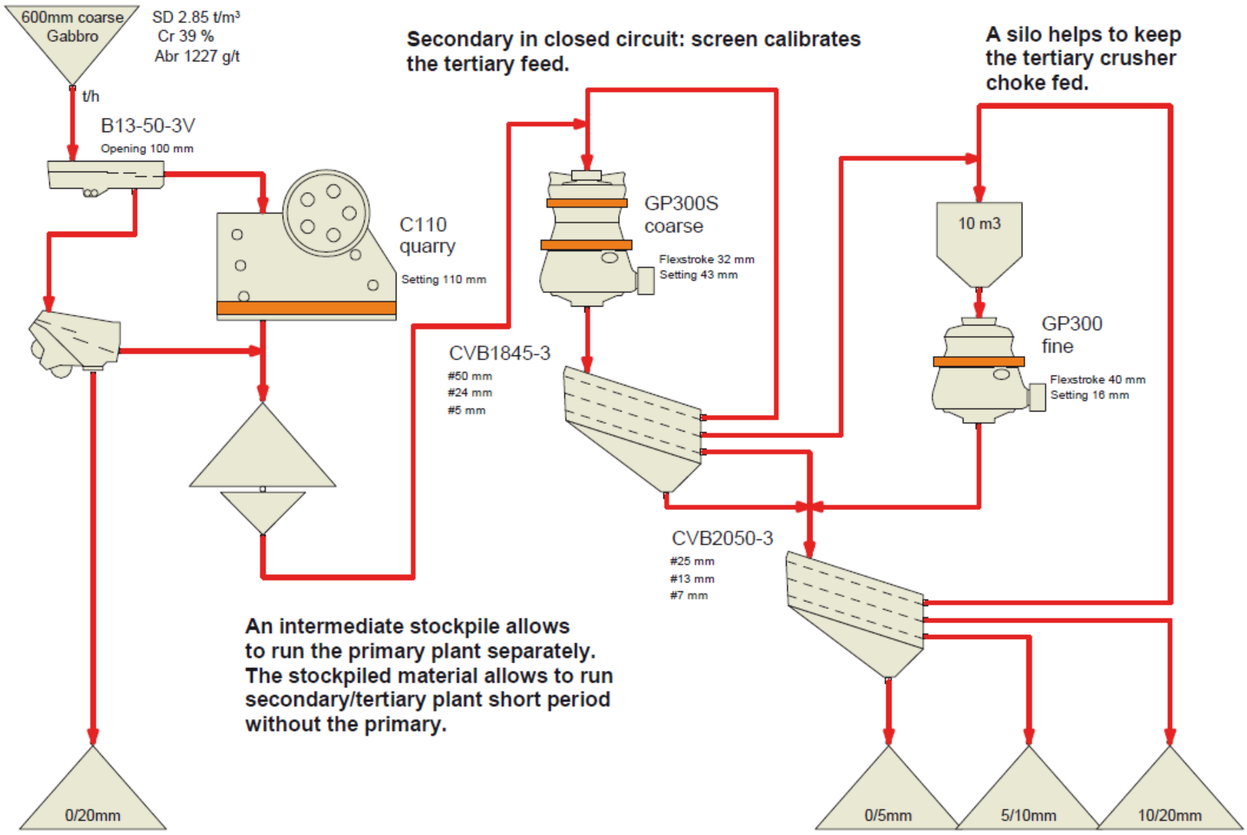

Figure 5: Process example 4: Asphalt aggregates – 330 tph.

5 Introduction to crushers

This chapter presents the basic principles of typical crusher types. More information can be easily found from manufacturers websites, e.g. www.metsominerals.com.

5.1 Primary crushing

Jaw crushers are mainly used as primary crushers. Their main purpose is to produce material that can be transported by belt conveyors to the next crushing stages. The crushing process takes place between a fixed and a moving jaw. The moving jaw dies are mounted on a pitman that has a reciprocating motion. The jaw dies must be replaced regularly, due to wear.

There are two basic types of jaw crushers: single toggle and double toggle. In the single toggle jaw crusher, as illustrated in Figure 6, an eccentric shaft is on the top of the crusher. Shaft rotation causes, along with the toggle plate, a compressive action. A double toggle crusher (illustrated in Figure 7, has, basically, two shafts and two toggle plates. The first shaft is a pivoting shaft on the top of the crusher, while the other is an eccentric shaft that drives both toggle plates. The moving jaw has a pure reciprocating motion toward the fixed jaw.

The chewing movement, which causes compression at both material intake and discharge, gives the single toggle jaw better capacity, compared to a double toggle jaw of similar size. The jaw crusher is a reliable and robust equipment, and therefore quite popular in primary crushing plants.

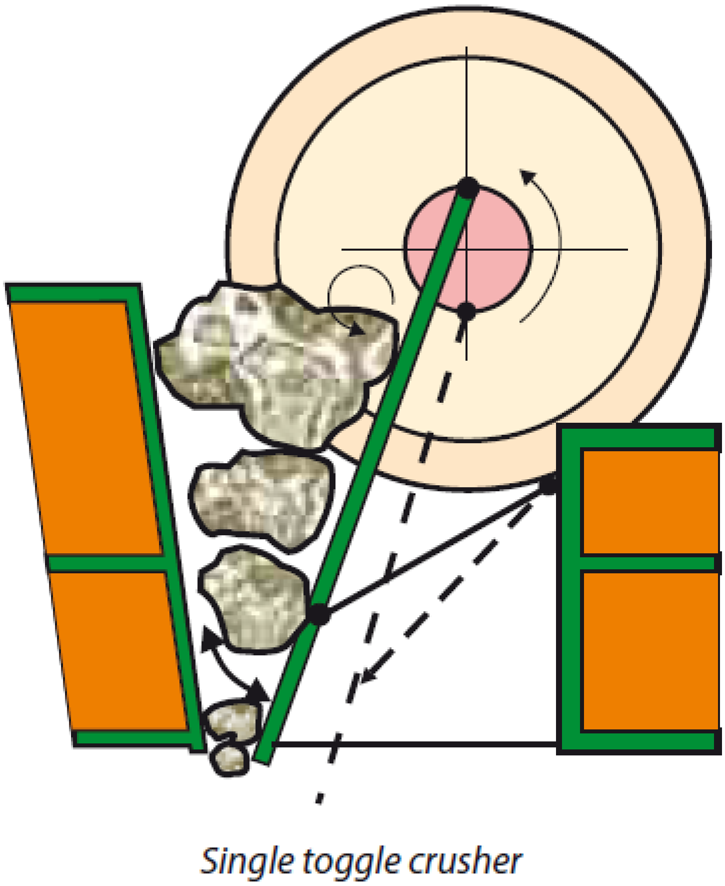

Figure 6: Single toggle crusher.

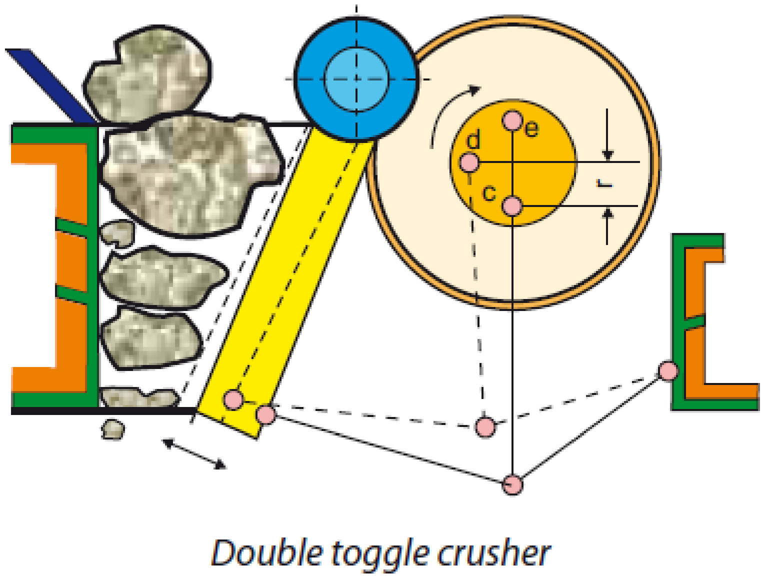

Figure 7: Double toggle crusher.

5.2 Cone and gyratory crushers

Both cone and gyratory crushers have an oscillating shaft. The material is crushed in a crushing cavity, between an external fixed element (bowl liner) and an internal moving element (mantle) mounted on the oscillating shaft assembly.

An eccentric shaft rotated by a gear and pinion produces the oscillating movement of the main shaft. The eccentricity causes the cone head to oscillate between open side setting (o.s.s.) and closed side setting (c.s.s) discharge opening. In addition to c.s.s., eccentricity is one of the major factors that determine the capacity of gyratory and cone crushers.

The fragmentation of the material results from the continuous compression that takes place between the liners around the chamber. An additional crushing effect occurs between the compressed particles, resulting in less wear of the liners. This is also called interparticular crushing.

The gyratory crushers are equipped with a hydraulic setting adjustment system, which adjusts c.s.s. and thus affects product gradation. Depending on cone type, setting can be adjusted in two ways. The first way is for setting adjustment to be done by rotating the bowl against the threads so that the vertical position of the outer wear part (concave) is changed. One advantage of this adjustment type is that liners wear more evenly. Another principle is that of setting adjustment by lifting/lowering the main shaft. An advantage of this is that adjustment can be done continuously under load. Some cone crusher models combine both adjustment methods.

To optimize operating costs and improve the product shape, as a rule of thumb it is recommended that cones always be choke-fed, meaning that the cavity should be as full of rock material as possible. This can be easily achieved by using a stockpile or a silo to regulate the inevitable fluctuation of feed material flow. Level monitoring devices detect the maximum and minimum levels of the material, starting and stopping the feed of material to the crusher, as needed.

5.2.1 Gyratory crushers

Primary gyratory crushers, as illustrated in Figure 8, are used in the primary crushing stage. Secondary gyratory crushers are normally used in the second crushing stage, but, in some cases, they can be used in the primary stage if the material has a size that fits the feed opening. Compared to the cone type secondary crusher, a gyratory crusher has a crushing chamber designed to accept feed material of a relatively large size in relation to the mantle diameter. Therefore, the cone head angle is smaller than that of a gyratory type of cone crusher.

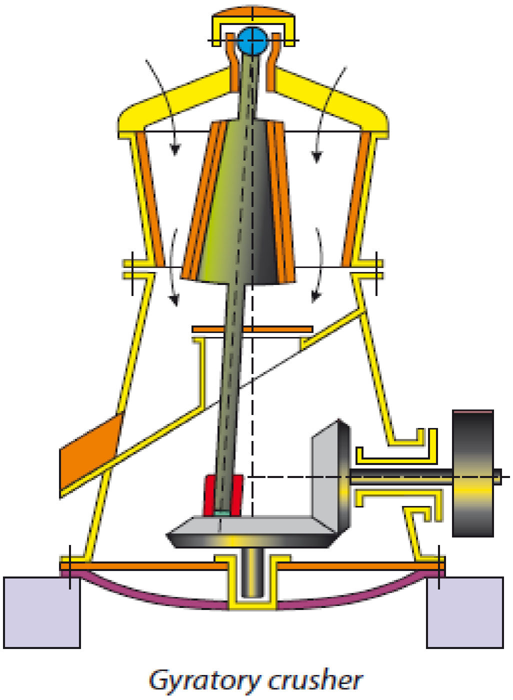

Figure 8: Gyratory crusher.

5.2.2 Secondary, tertiary and quaternary cone crushers

These cone crushers are used for intermediate or fine crushing, and/or to obtain a product with good cubical shape. The feed material receives primary crushing in previous stages. In the case of gravel, Mother Nature has done the primary crushing, and therefore the cone-type secondary crusher can, sometimes, carry out the complete crushing process. The key factor for the performance of a cone type secondary crusher is the profile of the crushing chamber or cavity. Therefore, there is normally a range of standard cavities available for each crusher, to allow selection of the appropriate cavity for the feed material in question.

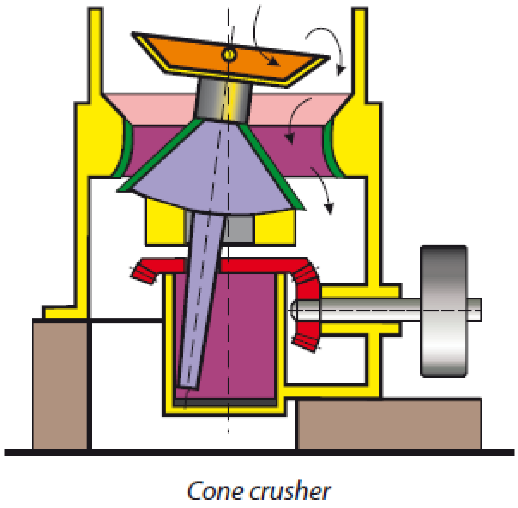

Figure 9: Cone crusher.

5.3 Impact crushers

The two main types (horizontal-shaft and vertical shaft impactors) are characterized by a high reduction ratio and cube-shaped product. The impactors can also be used for selective crushing, a method that liberates hard minerals from the waste material.

5.3.1 Horizontal-shaft impactors (HSI)

The feed material is crushed by highly intensive impacts originating in the quick rotational movement of hammers/bars fixed to the rotor. The particles produced are then further crushed inside the crusher as they collide against crusher parts and against each other, producing a finer better-shaped product.

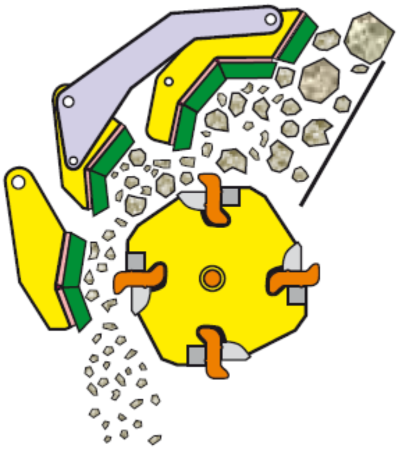

Figure 10: Impactor (HIS).

5.3.2 Vertical-shaft impactors (VSI)

The vertical-shaft impactor can be considered a ‘stone pump’ that operates like a centrifugal pump. The material is fed through the center of the rotor, where it is accelerated to high speed before being discharged through openings in the rotor periphery. The material is crushed as it hits the outer body at high speed and due to the rock-on-rock action. The autogenous VSI impactors as illustrated in Figure 11, use the rock-on rock crushing principle, thus minimizing wear costs.

The VSI crushers, as illustrated in Figure 12 with metal liners around the inner part of the body are used for low abrasion material grinding applications. These crushers offer higher reduction ratios at lower energy consumption than that of autogenous models. The VSI crushers are mainly used in the production of fine materials, including sand with a good cubical shape.

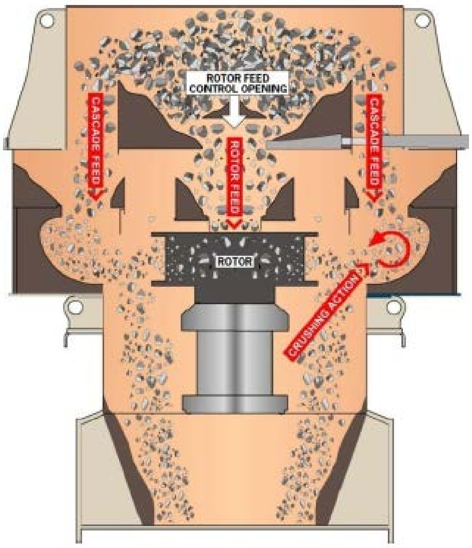

Figure 11: Autogenous Impactor (VSI).

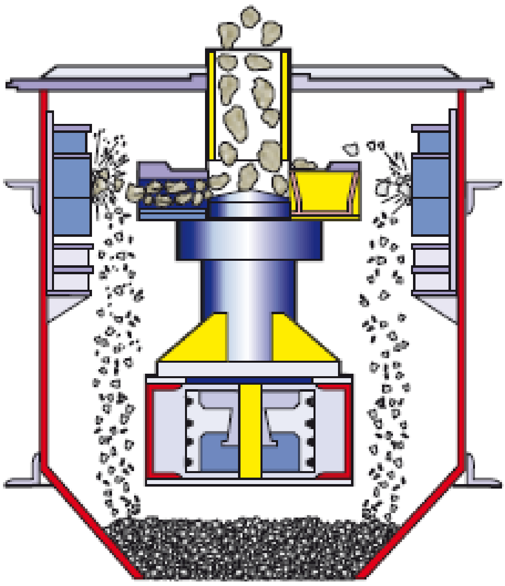

Figure 12: Impactor (VSI).

5.4 High Pressure Grinding Roll crushers

The High Pressure Grinding Roll (HPGR) is a technology that was conceptualized in the 1980's for crushing industrial minerals. Since, it has been developed for mining and later also for aggregate applications. Within the last 10 years, HPGR technology has increased in popularity in aggregate production. However, in aggregate applications extremely high pressures are not typically utilized, but medium operating pressures. Still, HPGR's high operating pressure and rock-on-rock crushing principle allows much finer product grading and better product shape comparing to traditional low-pressure roll crushers. HPGR's can make fine sand even from very hard rock material in closed circuit operation.

HPGR is also suitable for processing moist and zero-based feed materials from waste stockpiles without preprocessing.

In HPGR's product curve is adjusted with applied pressure that is a difference comparing to e.g. cone crusher or traditional roll crusher.

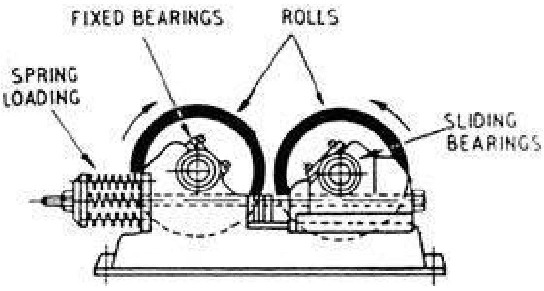

Figure 13: Traditional low-pressure roll crusher.

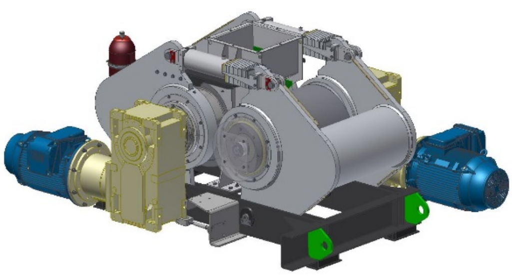

Figure 14: High pressure roll crusher.

6 Aggregate cleaning, screening and classifying

Besides crushing, the ways of sorting, or sizing, the products will be determinant for the final product quality. Basic overview of methods for sorting, sizing and classifying aggregates is available in several textbooks, e.g. Smith & Collis [17]. Specifications for modern equipment will further be available on producers' websites, e.g. www.metsominerals.com.

6.1 Air classifiers

Air classifiers are predominantly used in mobile applications due to their mobility and compact size. Air classifiers can be divided into dynamic and static units, by the way how the classifier works.

Dry classification of filler is generally done using air. This involves moving air currents through free falling manufactured sand. The lightweight particles are effectively removed and transported to an independent separation stage. The filler can then be classified as either a general-purpose product or, as some innovative aggregate producers are doing, treating this material and selling it in new and exciting industry applications. Air classified sand in a mobile crushing plant must be handled and stockpiled with care to avoid segregation at final use, like concrete plant, see chapter 7 Aggregate storage and handling.

6.1.1 Dynamic air classifiers

Sturtevant Inc.'s Whirlwind Air Classifiers use an internal fan and rejecter blade classification system. The feed is belt conveyed into the classifier by gravity. De-dusted manufactured sand exits the system by gravity for belt conveying to the clean pile. Dry, minus 0.075 mm fines also exit the classifier by gravity at a single outlet for belt conveying to a fines by-product pile. Rotating selector blades control the particle size of the fines removed by the air. According to the manufacturer, this improves the dusted product yield, when compared to static air classifiers.

Sturtevant air classifiers balance the physical principles of centrifugal force, drag force and gravity to generate a high-precision method of classifying particles according to size or density. For dry materials of 0.152 mm and smaller, air classification provides the most effective and efficient means for separating a product from a feed stream for de-dusting, or for increasing productivity when used in conjunction with grinding equipment.

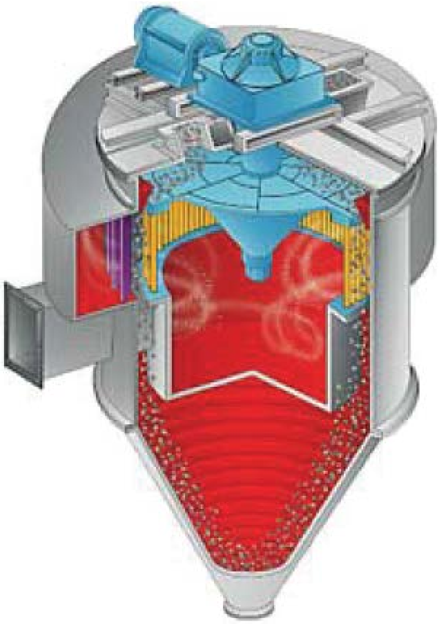

Figure 15: Dynamic air classifier.

6.1.2 Static air classifiers

One of the manufacturers of static air classifiers is Metso. When rock material is abrasive, static air classifiers are a cost-effective and consistent separation alternative for removing –0.063 mm filler from manufactured sand. This is due to not having wearable items in the material flow affecting separation efficiency, and ceramic lining mainly protects the wearable items. The Metso Air Classifiers (Figure 16) combine gravitational, inertial, centrifugal and aerodynamic forces to efficiently classify materials at cut points ranging from 300 to 63 microns. The feed material and primary air enter the top of the unit and travel downward. The air makes a 120° change in direction. It then exits through the vanes carrying fine particles with it. The coarse particles being too heavy to make the turn fall to the bottom where they pass through the secondary air before they are discharged through a valve. Secondary air, entering below the vanes, passes through the curtain of falling particles. The secondary air stream into an eddy current within the heart-shaped chamber diverts those particles that are near cut point in size. Some fines are captured as they enter the unit while others are drawn from the eddy. The exiting air to a fabric filter for final recovery carries these.

The Metso centrifugal classifier units (Figure 16 to the right) employ centrifugal forces, similar to cyclones, to separate particles at cut points between 20 and 100 microns. A series of internal baffles apply drag forces to the coarse particles while allowing air to pass through them, resulting in separation of the fines. The heaviest particles drop to the bottom of the classifier where they are discharged through a valve. Prior to the discharge, secondary air is injected and passes through the material, and particles near the cut point in size are returned to the circulating chamber. The fine particles travel a spiral path into the outlets located on each side of the unit. The two air streams combine and enter a cyclone for final recovery of fine particles. The size of the fines is controlled by adjusting the equipment. Free water content of pulverized material when present on the surface of the particles changes the apparent particle size distribution of the classifier feed by forming agglomerates. The free water content tolerated by air classifying devices depends entirely on the nature of the material being classified.

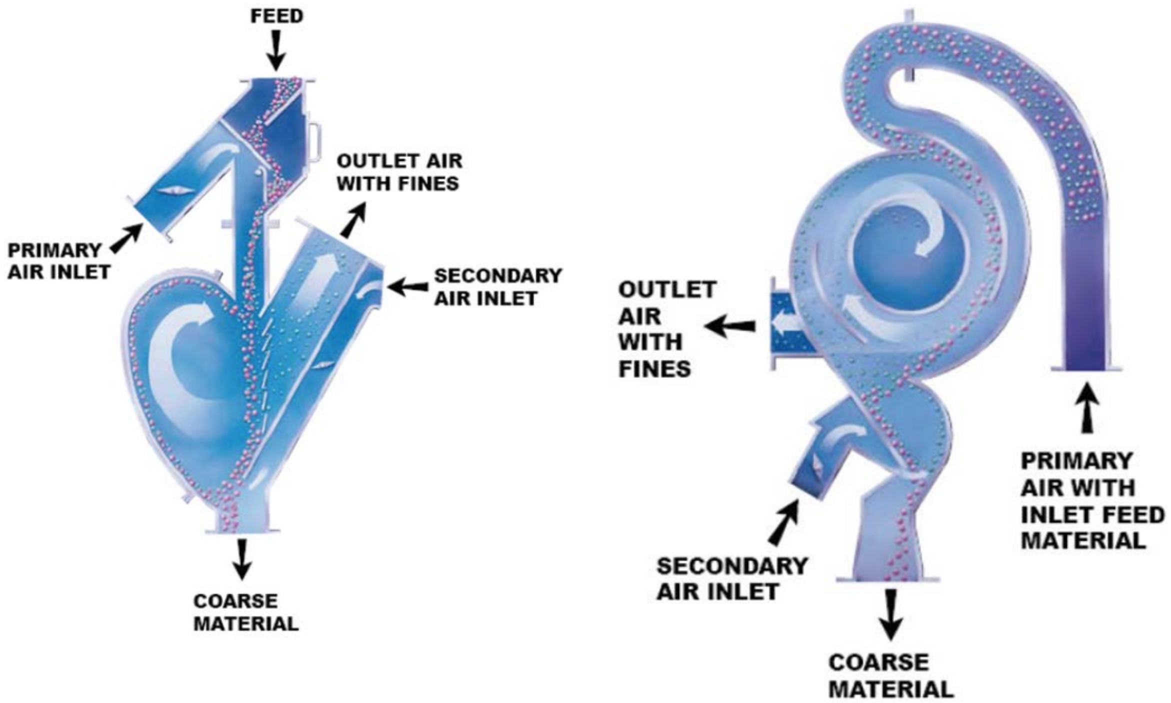

Figure 16: Metso static air classifier models Gravitational Inertial and Centrifugal.

7 Aggregate storage and handling

Aggregate storage is one of the most important things for quality ensuring. Although the aggregate would be of even quality from the production, improper storage can cause large quality variations or even prevent using it [18]. This is especially the case for concrete aggregates and sand. Concrete recipes are sensitive against grading and quality variations. Whenever the quality of the aggregate changes, the concrete plant must adapt the concrete recipe, which will cause further work at the factory and at worst case unusable concrete patches. When storing aggregates, methods must be used to avoid the segregation or accidental contamination of the aggregates. Storage is followed by local guidelines. The storage location is chosen so that the area's load capacity is sufficient, and the bottom is flat. It is recommended to put about 20 cm layer of finer aggregate in the bottom of the stockpile. This prevents the stockpile area base material and stored rock material mixing. As a stockpile base, light colored aggregate can be used, such as limestone. In this case, when the aggregate is reclaimed from pile, it is clearly visible. The storage area must be so wide that the piles are clearly separated from one another to avoid material mixing. Adequate gap spacing guarantees safe and smooth operation of wheel loaders and trucks.

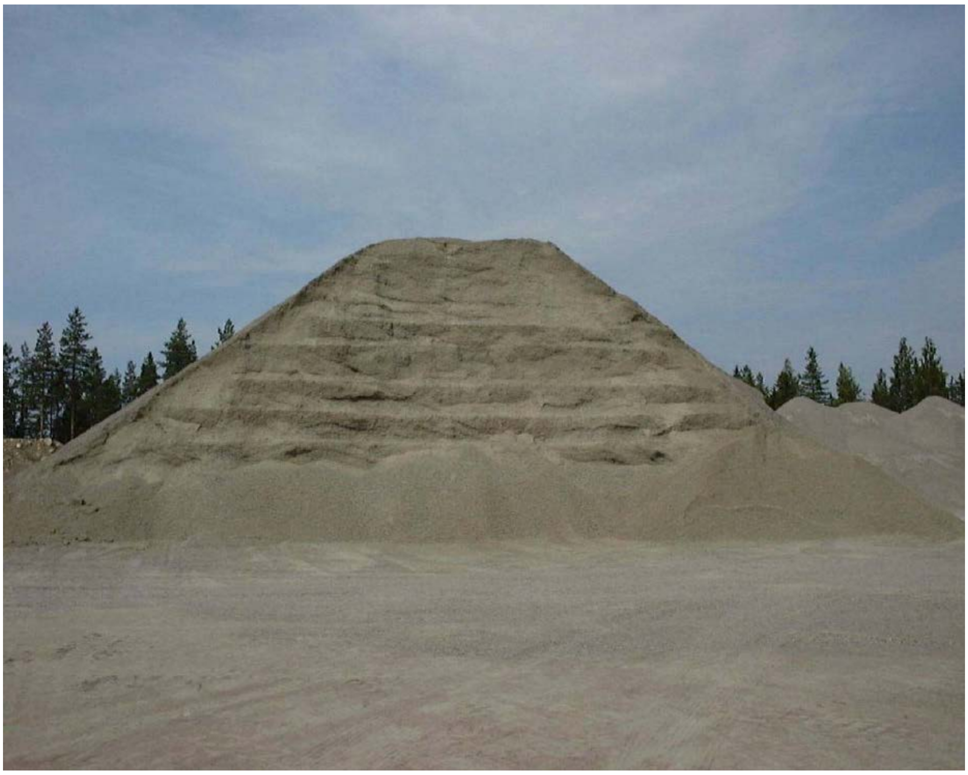

Figure 17: Aggregate stockpile made layer by layer.

When the aggregates are stored in layers, the homogeneity of the product is improved, but on the other hand, the aggregates may be degraded at the driveways. Figure 17 shows a stockpile made layer by layer. Degraded parts of the product stock must be removed at the time of loading of the material.

In storage, it is always necessary to avoid contamination, for example large stones or pieces of wood. When storage time is long, it can get mossy and around the pile begins to grow plantation. This raises the content of organic material and prevents the use in ready-mixed concrete. In wintertime it is needed to remove snow and frozen lumps before loading the trucks [19].

8 Crushing, screening and classifying equipment limitations and possibilities on mobile platforms

There are two kinds of mainstream mobile crushing and screening units: portable (wheel mounted) and track mounted. Not like portable plants, track mounted mobile crusher for aggregate production is a relatively new invention. The first models were introduced in 1985 both in Norway and Finland. Reasoning in Finland was forest road building in remote locations, where the upcoming boulders and solid rock had to be crushed. In Norway track mounted primary crushers were used e.g. in tunnel projects. Conducting primary crushing with a compact unit inside the tunnel made material hauling out from tunnel much easier compared to handling bigger sized blasted rock.

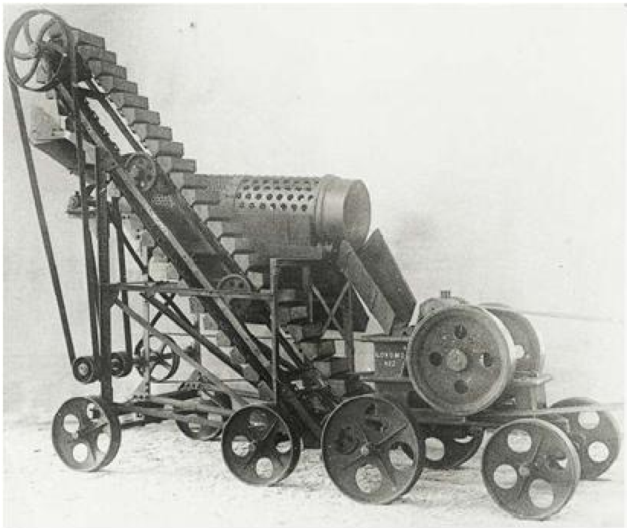

Figure 18: Mobile crushing and screening plant from the early days.

8.1 Flowsheet possibilities with highly mobile track mounted equipment

Figure 19: Highly mobile track mounted crushing plant.

Mobile crushers are widely used for producing road building materials close to the final place of use of aggregates. Typical road structure is shown in Figure 20.

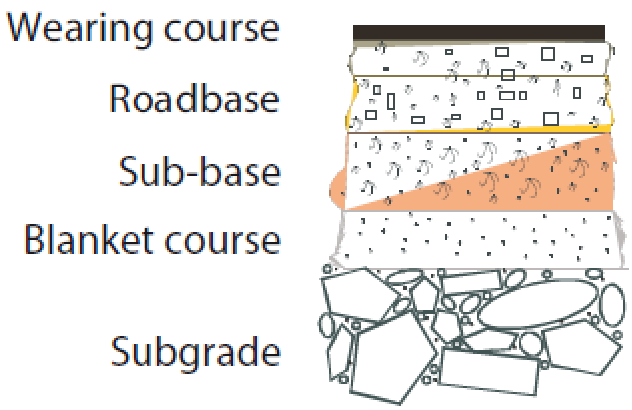

Figure 20: Typical road structure.

Subgrade in Nordic countries is more and more primary crushed material instead of blasted rock. Mobile crusher is very suitable for the production.

Subbase is typically produced with two mobile units; primary unit with grizzly feeder +jaw crusher and secondary unit equipped with on-board screen and cone crusher. Typical flowsheet is shown in Figure 21. Note that in each picture the equipment inside the light blue rectangle is one mobile crusher unit.

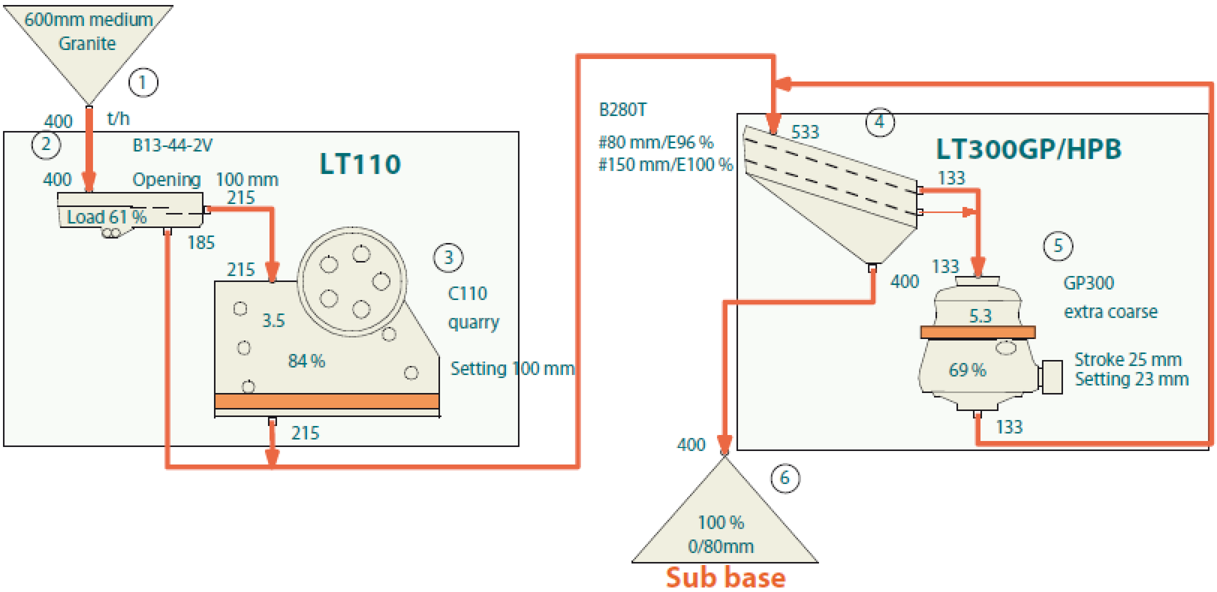

Figure 21: Typical subbase production flowsheet.

Below are examples of flowsheets for road base material production in case of easy and difficult materials, respectively. Nowadays with more powerful crushers, road base is produced with high capacity also with previous lay-out with two mobile crusher units.

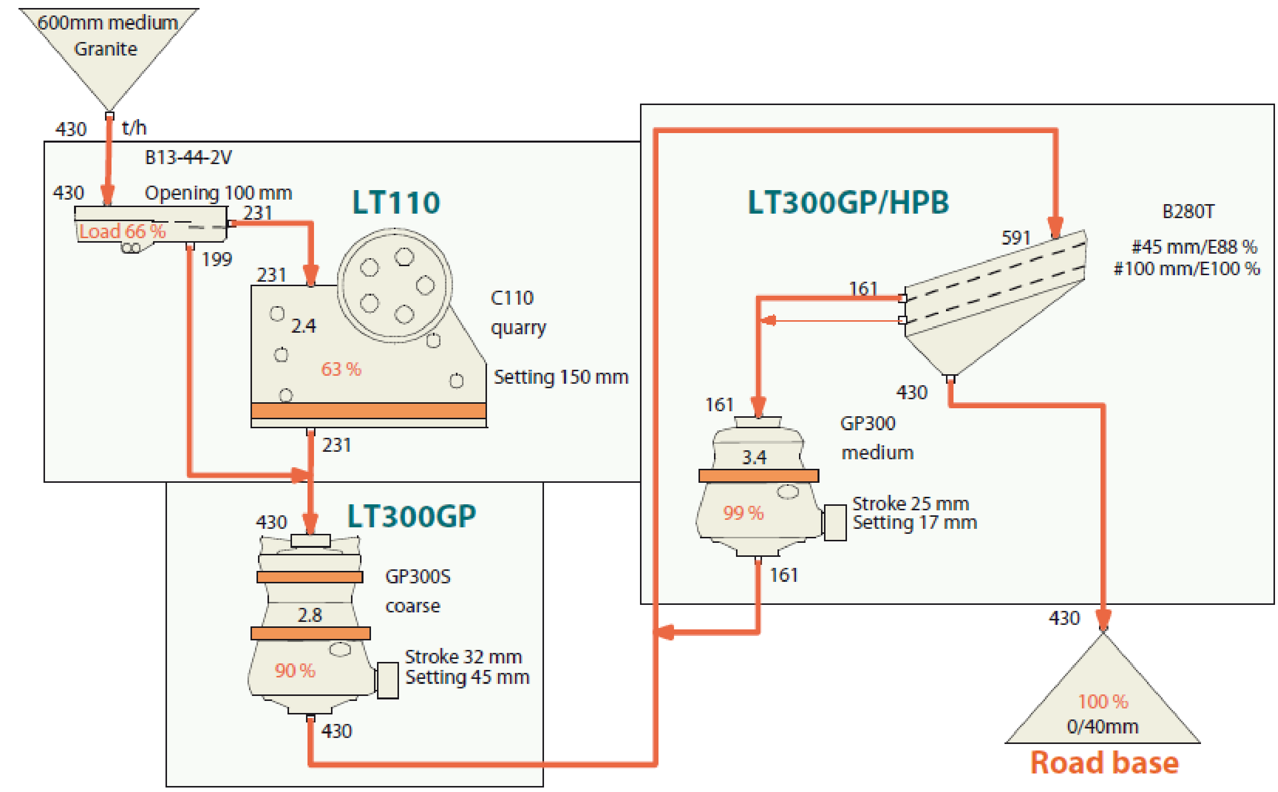

Figure 22: Typical road base production flowsheet when material is easy.

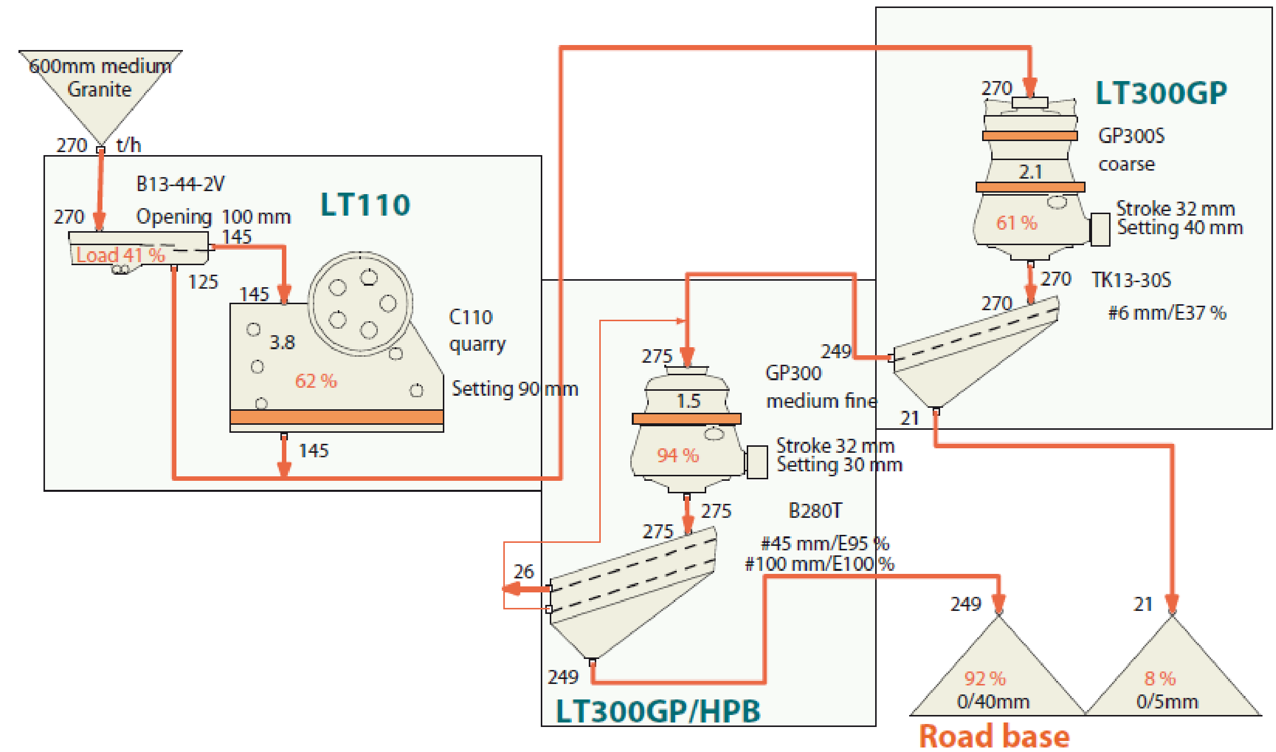

Figure 23: Typical road base production flowsheet when material is difficult.

In asphalt aggregate production, depending on feed material properties and asphalt, aggregates are produced in different ways. In Figure 24 and Figure 25 is shown typical three-unit production line.

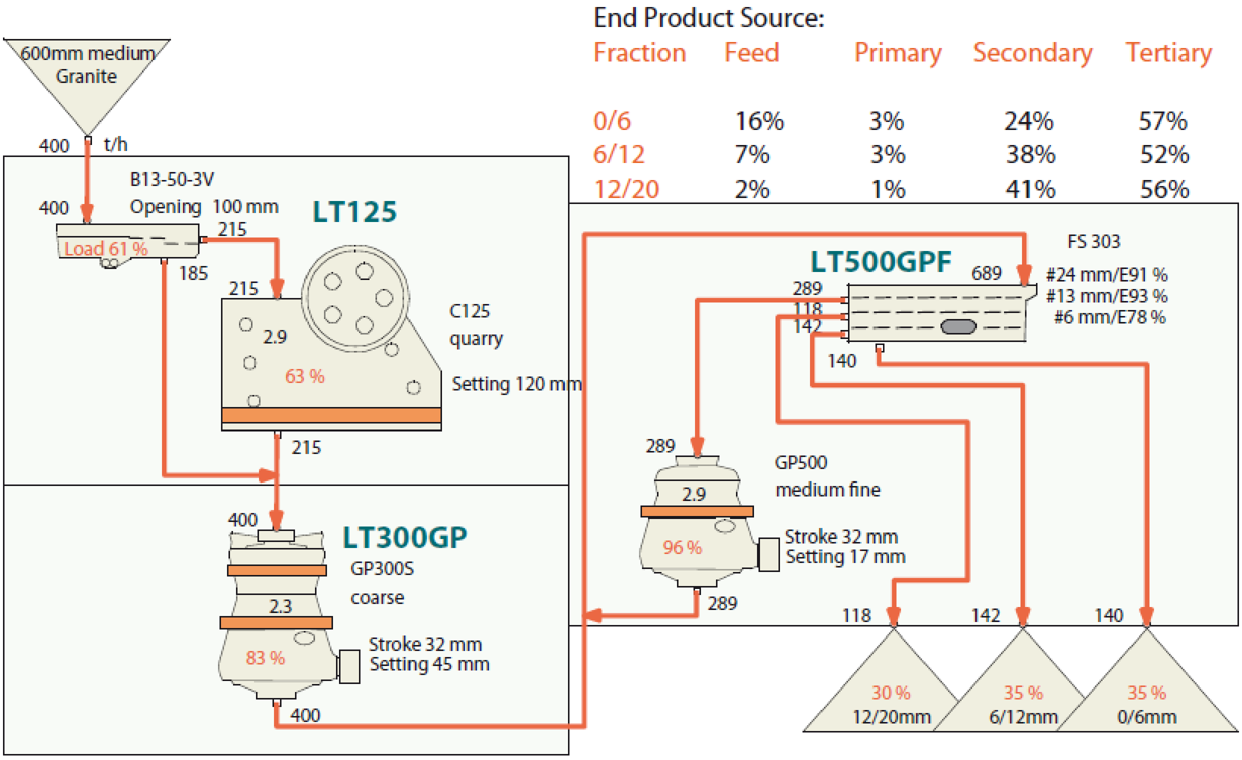

Figure 24: Asphalt aggregate production, lower quality or easy material.

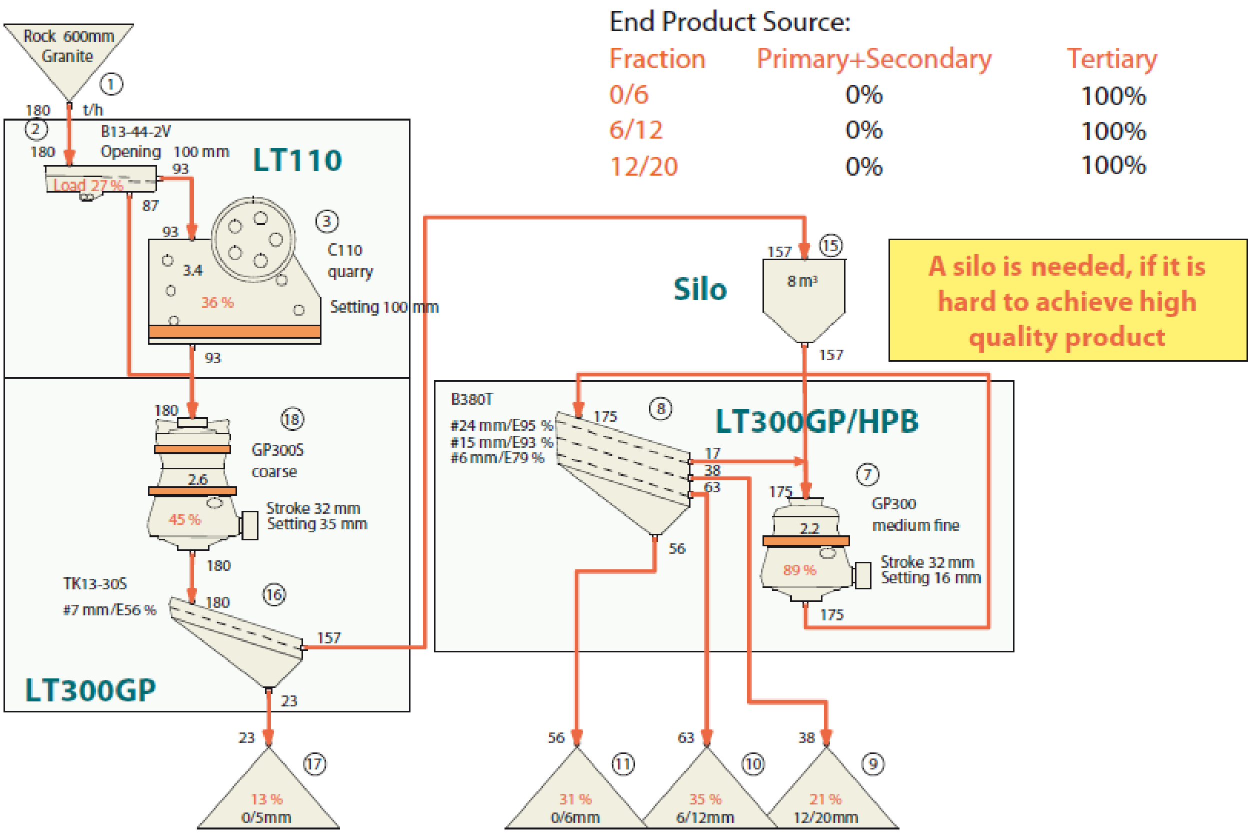

Figure 25: Asphalt aggregate production, high quality and/or difficult material.

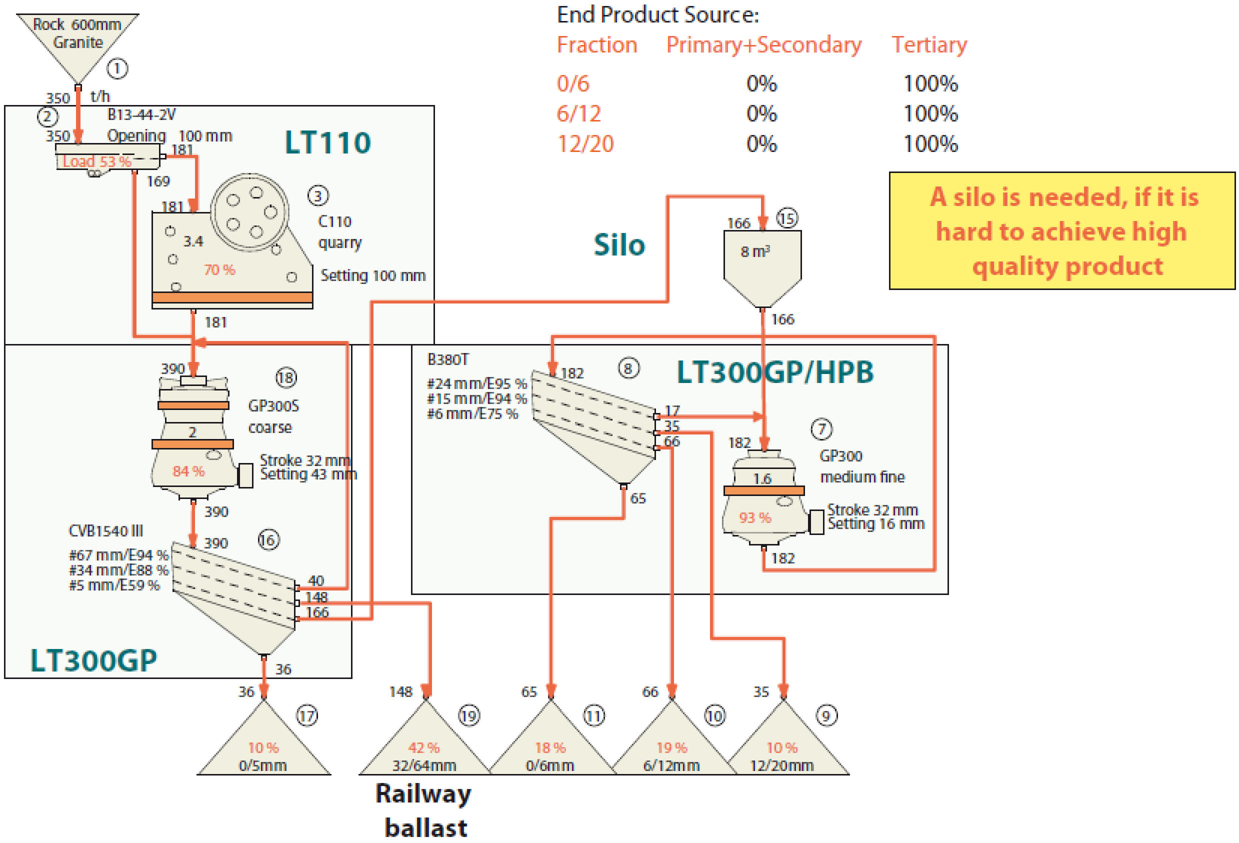

Figure 26: Combined railway ballast and high quality asphalt production.

8.2 Aggregate quality achieved with highly mobile track mounted equipment

Aggregate quality, consistency and production capacity is affected by crusher load. Consistent crusher choke feeding minimizes these variations. This can happen by utilizing surge bins or alternatively by using especially for mobile crushers and screens developed automation systems.

Latter option is increasingly common while surge bins restrict crushing plant mobility. The idea in mobile crusher automation is to keep selected crusher; typically tertiary cone crusher in ideal choke feed condition automatically. Automation is simply said adjusting primary unit feeder based on level sensor or crusher feedback. Time delay from primary feeder to tertiary cone crusher feed hopper can be rather long. Thus, in modern mobile plant automation systems e.g. load on conveyors are monitored to reach accurate enough control of choke fed tertiary crusher. It is also possible to adjust manually feeder speeds and settings of the crusher, like CSS. Data exchange between mobile crusher units and feeding machine is typically realized by wireless connections.

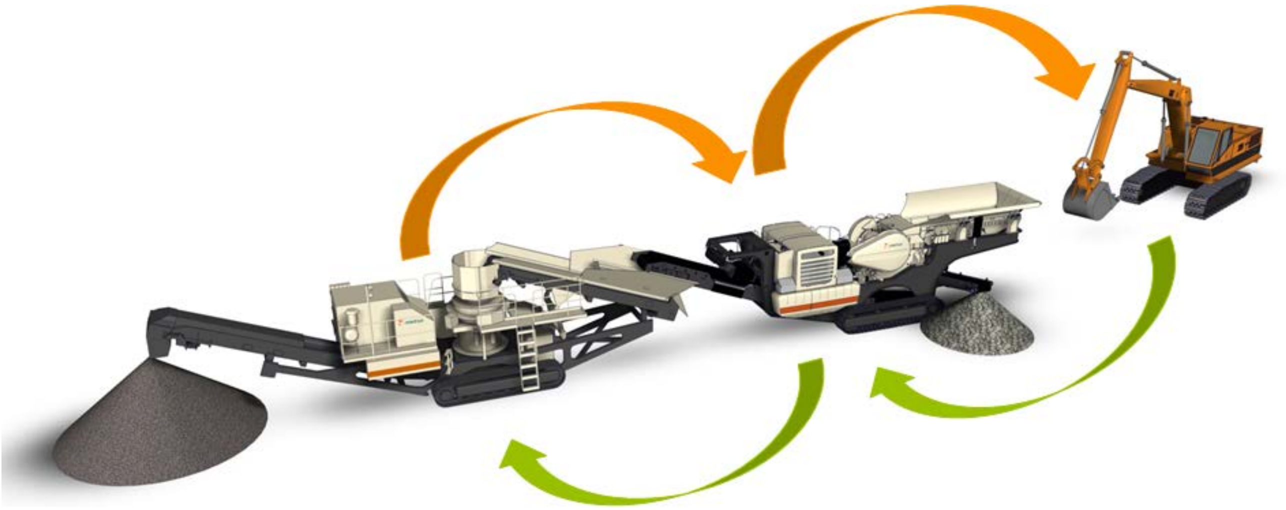

Figure 27: Data exchange between machines.

Figure 28: Crushing process control from excavator cabinet.

Figure 29: Portable crushing plant. Flowsheet possibilities.

Wheel mounted / portable plants are the second mainstream mobile plant concept. Typical portable plants include separate process conveyors meaning plant built-up time during relocation is typically starting from some hours to 2 days depending on plant complexity and type of the equipment. Also, footprint requirement is more comparing to a track mounted plant, and an external power source is required (diesel gen set or grid electricity). On the other hand, portable nowadays consists of surge bins and high flexibility regarding to flowsheet options. Also, portable plant unit equipment selection is wider, including e.g. high-pressure roller crusher and air classifier. This means, portable plants can produce also the highest quality and special products in a consistent way. Due to the high number of variants available, typical flowsheets are not presented here, but two special equipment's and some words about automation possibilities are included.

Figure 30: Metso portable High-pressure roller crusher.

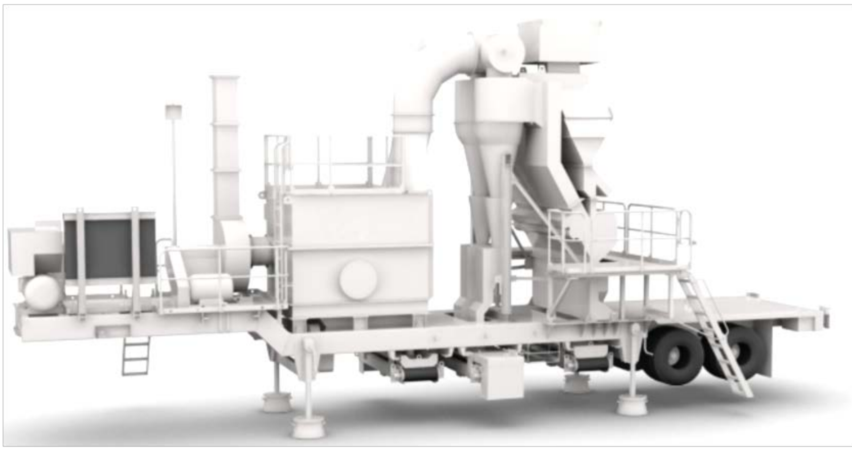

Figure 31: Metso portable static air classifier for ultra-fines removal.

8.3 Aggregate quality achieved with portable crushing plants

Aggregate quality, consistency and production capacity is affected by crusher load. Consistent crusher choke feeding minimizes these variations. This can happen by utilizing surge bins or alternatively by using especially for mobile crushers and screens developed automation systems.

Regarding portable plants, crushing plant control strategy is nowadays towards combined automation and surge hopper design. The idea in a portable plant is to keep the selected crusher, typically tertiary cone crusher, in ideal choke feed condition automatically. Process control is simply said done by adjusting surge bin feeder based on level sensor or crusher feedback. And surge hoppers are to homogenize material flow rate variations originating from primary crusher and ROM. Automation system itself can be a centralized plant automation with control cabinet or autonomous system. In both ways, a single portable unit intelligent controller, sensing the crusher load and product surge hopper enabling consistent plant operation, controls the portable plant. Centralized control room allows easier equipment and process parameter adjustments without need to enter separate portable units. See Figure 32 for example of crushing process control activities.

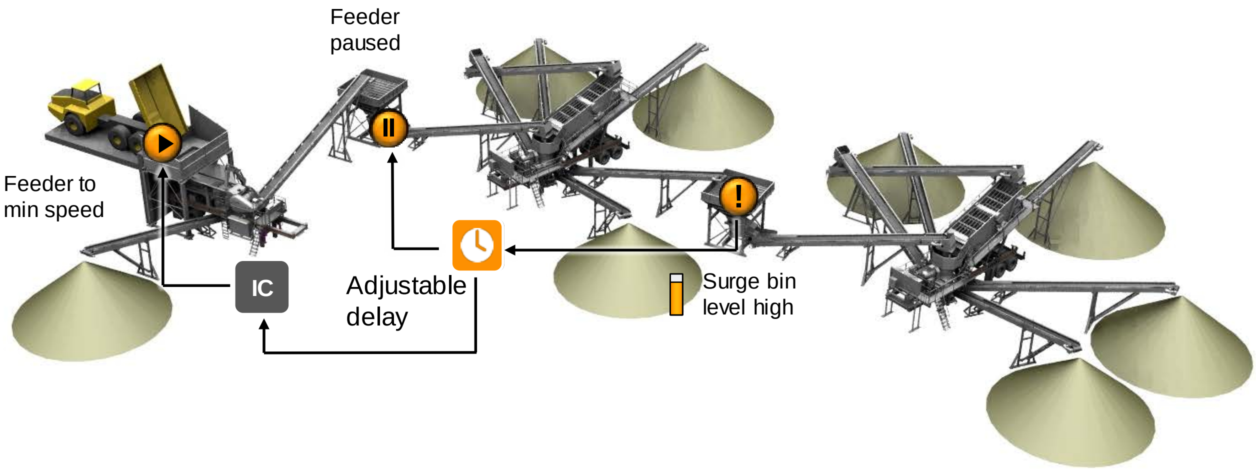

Figure 32: Functionality of a portable plant Intelligent Control, case tertiary crusher feed surge bin level high.

9 Summary and conclusion

The present report arguments for the use of local/short-travelled aggregates due to the following:

- Economy
- Sustainability, and
- Resource management.

It is vital for such use that the aggregates can be excavated and processed effectively following the development of e.g. an infrastructure process. A major part of the report is therefore devoted to aggregate processing.

Aggregates should be prioritized based on geological conditions in a bottom-up concept. This means that when considering local and/or short-travelled alternatives, the design and engineering solution should be based on the aggregates available – not the other way around, which is often the case today.

This will apply to infrastructure projects – aggregate solutions along the line (excavations, tunnel blasting), as well as so called quarry waste at locations close to the line (e.g. dimensional stone quarries). Application technology for rock materials can preferably include materials design to make use of secondary quality materials, e.g. in bottom or subbase layers, while the more high-requirement aggregates are spared for the top layers in a road structure.

The geological differences and the often unpredictable variations are clearly among the major challenges for a short-travelled solution. The report highlights the aggregate technology triangle in order to see the geology – production – application interconnection, for the creation of good solutions. The Best Available Concept (BAC) can be a tool for prioritising sustainability and resource management, see Figure 33.

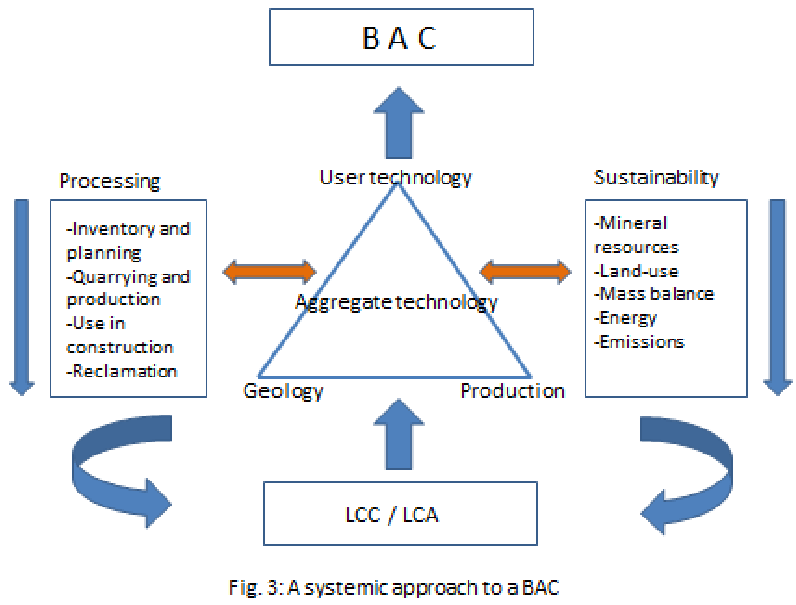

Figure 33: A best available concept for aggregate production and use [1].

The set of novel processing technologies available, present the opportunities to transform theoretical knowledge into practical aggregate production. Especially, the portable processing equipment and technology opens for solutions to produce purpose adapted, local/short-travelled aggregates.

The report gives a presentation of the basic kinds of crushing and sorting equipment, along with processing examples for different user-purpose. Several flow-sheets for mobile processing of different kinds of product are presented and discussed.

Finally, it is worth noting that today most processing equipment is available on portable platforms, and that these platforms can be combined into effective processing systems.

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