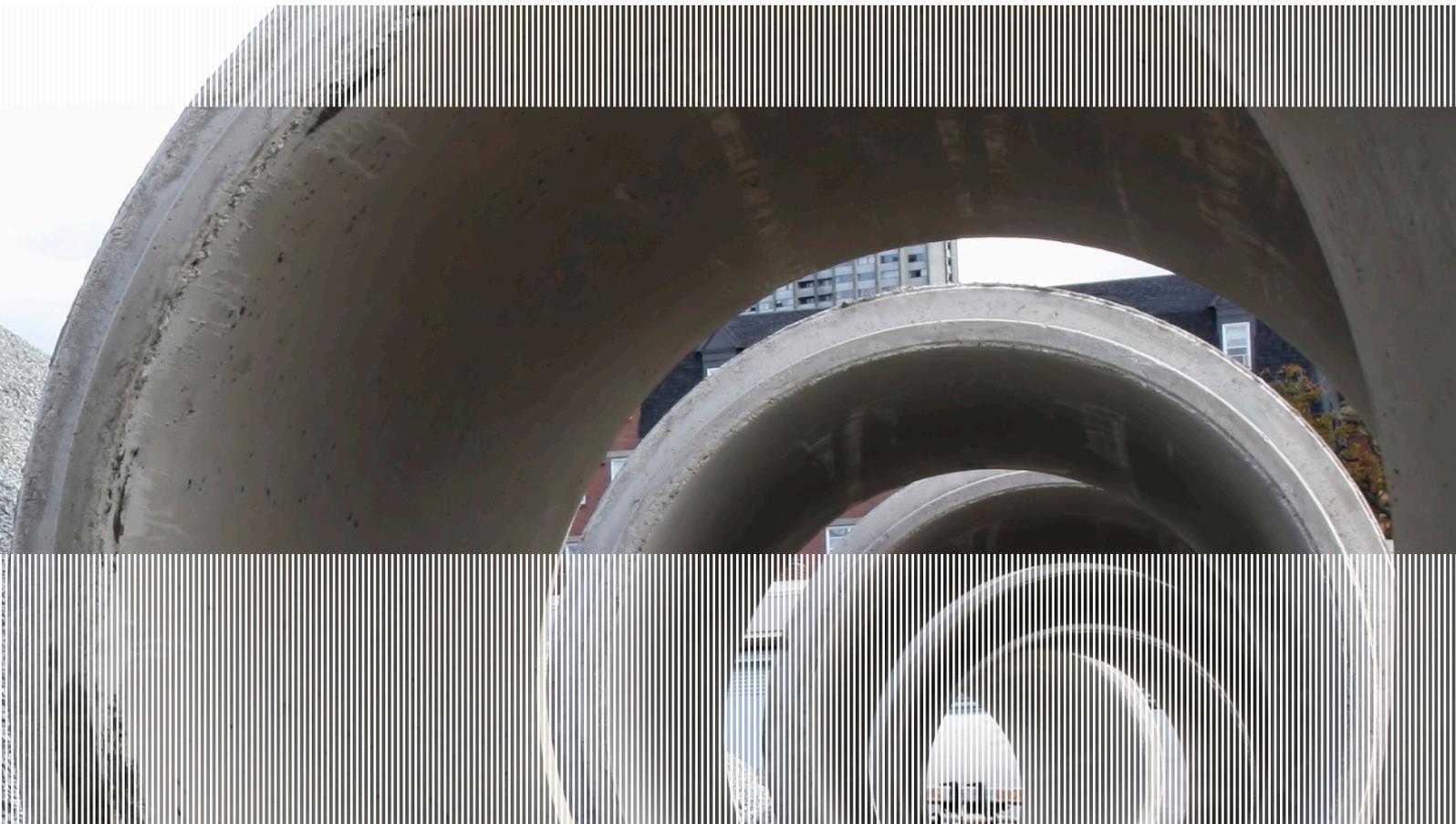


SINTEF Building and Infrastructure Børge Johannes Wigum, Svein Willy Danielsen (editors)
Odd Hotvedt & Bård Pedersen

Production and Utilisation of Manufactured Sand

State-of-the-art Report

COIN Project report 12 - 2009



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COIN P 2 Improved construction technology

SP 2.5 Production of manufactured sand

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Keywords:

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Preface

This study has been carried out within COIN - Concrete Innovation Centre - one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfil this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology - NTNU (research partner) and industry partners, 15 - 20 PhD-students, 5 - 10 MSc-students every year and a number of international guest researchers, work on presently 5 projects:

- Advanced cementing materials and admixtures
- Improved construction techniques
- Innovative construction concepts
- Operational service life design
- Energy efficiency and comfort of concrete structures

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %).

For more information, see www.coinweb.no

Tor Arne Hammer
Centre Manager

Summary

This State-of-the-art report has been compiled through extensive search of relevant literature and through information and experience provided by international experts. The report deals with the production and use of manufactured sand, which is defined as aggregate material less than 4 mm, processed from crushed rock or gravel, intended for construction use. The motivation for this project is the increased miss balance between the need for aggregates in the society and the need to develop concept solutions for the use of manufactured sand as concrete aggregate.

The intension of this project is based upon a holistic approach, looking into the whole concept including; environmental issues, mineral properties, sampling and testing, production processes, specifications and new development in concrete mix design involving the latest generation of admixtures.

Environmental issues

Aggregate production is, by the strictest definition, non-sustainable, since aggregate resources are non-renewable. However, sustainability could be achieved by optimizing the whole production process, leading to a maximum of added value to the society, without causing a need for re-deposition or pollution. The real challenge will be to merge the environmental issues with the industrial ones; to create industrial 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.

As natural aggregate resources near urban centres terminate, the transport distances increase. This is already the situation in urban areas in Norway. Even though production of manufactured sand requires more energy than corresponding production of natural sand, the vicinity to the market, with less transport, will make manufactured sand environmentally favourable.

Mineralogical properties – sampling and testing

When producing manufactured sand, it is possible to select the raw material, i.e. the parent rock. Properties of the parent rock are determined by various petrological parameters that have an important influence, both upon the blasting and crushing of manufactured sand, e.g. energy consumption, fines production and shape, but also upon the quality of fresh and hardened concrete.

In order to tailoring the end product for specific purposes, it is important to know how these properties are influencing the end product. It is e.g. experienced that lithology has not so much impact on geometric properties for the sand fraction, i.e. 63 μm - 4 mm; however it may govern these properties for the fines. The effects of secondary minerals on properties and quality of the fines, for use in concrete, are only partly known. This needs to be examined further. A variety of test methods exist, but the industry requires development of sufficient and accurate test methods for fine aggregate. It is in particular important to examine the interaction of properties of fines and the effects of the new generation of concrete admixtures. In addition, it is necessary to define procedures for sampling, handling and testing for quality control purposes to ensure that the “right” material is being tested. Accurate classification of manufactured sand, including fines, will assist the whole industry to e.g. select proper raw material, suitable production equipments and a suitable concrete mix design procedures.

Production processes

In order to reach a high-quality final result, each crusher stage needs to be optimized – it is not a good approach to try to repair an insignificantly crushed product by the final crusher stage alone.

The installation of Vertical Shaft Impactors (VSI) has proved to be an effective way of producing cubical (even rounded) particles in the small and medium size fractions (< approx 5 mm). It is however a challenge to avoid generating of a high percentage of fines. The latest generation of dry screening equipment combined with the latest development of air classification have, however, enabled to govern the grading curve very precisely, including the finest part. Configurations of machinery from e.g. Metso/Buell or the V7 concept from Kemco in Japan are good examples, where manufactured sand has been produced for 100% use in concrete.

However, it is important to realise that high quality aggregates could be degraded by insufficient procedures of handling and storage.

Specifications

Current specifications in many countries still are based on the use of natural sands, where several specifications do not allow high percentages of fines to be used in concrete. A new understanding of the properties of manufactured sand, and the need to treat it differently is required.

Application in concrete – Design of concrete mixes

The difference in surface texture, shape properties and particle surface texture indicates that natural and manufactured sands are two different types of material and must be treated accordingly. These facts require development of new concrete mix designs, and knowledge for the application of this material. Experiences of traditional concrete mixed design based on natural sand should not be automatically transferred into this new material.

The R&D and tradition of using manufactured sand in concrete has been driven by need in different countries. This implicates that the practice differs in various parts of the world. Japan is an example of a country that early started developing and applying new technologies, since their natural sand resources got depleted many years ago. On the opposite side, North American – especially Canadian – resource conditions have been (and still are) of an order that do not call for alternatives to glaciofluvial sand/gravel as aggregate. In other countries, such as Australia, manufactured sand is seen as an appropriate substitute for natural sand, but it is claimed that it appears difficult to only depend on 100% manufactured sand. In Norway manufactured sand has both been applied in blends with natural sand and as 100% fine aggregate.

It must be our ambitions for the future to enable 100% use of manufactured aggregate in concrete, producing high quality concrete, both in the fresh and hardened state.

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1 Introduction

This State-of-the-art report is carried out as Sub-project no 2.5, as part of COIN Concrete Innovation Centre at SINTEF.

The report is based upon an extensive search of information, available on this topic, both nationally and internationally. In addition important information was obtained at an international workshop, arranged by the steering committee of this sub-project. The workshop was arranged in Stavanger on October 30th and 31st 2008. All the presentations of the workshop are compiled in a COIN report (2009) produced by the sub-project (Wigum, 2008)¹.

Part of chapter 5 is based upon previous work presented in a report by Wigum et al. (2004)².

1.1 Principal objectives and scope

The main aims of this report are to present state-of-the-art knowledge regarding production and utilisation of manufactured sand. The overall objective is to develop a technology platform for the shift from natural to manufactured aggregates based on hard rock. This includes knowledge of resource management, cost effective production, use of manufactured aggregates in concrete and mix design concepts for concrete.

1.2 Background - Why Manufactured Sand

The motivation for this project is the increasing miss balance between the need for aggregates in the society and the availability of traditionally suitable geologic sources. A strong need is realised for developing and implementing technology that can enable the use of alternative resources, reduce the need for transport and present zero waste concepts for the aggregate and concrete industry.

Aggregate producers are faced with constant demands for higher quality aggregates and, at the same time, have to take environmental issues into account. The most pressing issues being the excess amounts of fines (< 4 mm) following the crushing process for manufactured aggregates and the depletion of natural aggregate resources. Excess fines were, and in many countries still are, considered waste and were disposed of accordingly, at great costs and contamination. Producers recognised an unused opportunity and experimented with manufactured sand from gravel and crushed rock. Of advantage is that such sand has rough surface texture and the Particle Size Distribution (PSD) curve can be adjusted when the material is manufactured. In addition specific properties can be selected by selecting the source rock material. Extensive research programmes have been carried out, where properties of manufactured sand and usability in concrete have been the main focus. The results have in general been in favour of using manufactured sand, given the right conditions concerning rock type and production process. However, design parameters are different compared to natural sand. A development has been realised, from trying to duplicate the properties of natural sand, to production of a new product with new and improved properties.

Another advantage when sand and aggregates are manufactured is that quarries can be kept in the near vicinity to its place of end-use, thereby shortening transport distances, followed by less pollution and increased employment opportunities for the locals.

It is anticipated that in the future aggregate production from crushed rock will increase and production from natural sand and gravel deposits will decrease.

1.2.1 *Manufactured Sand - Definitions*

In this report the term *manufactured sand* is used for aggregate material less than 4 mm that is processed from crushed rock or gravel and intended for construction use. Manufactured sand is a material of high quality, in contradiction to non-refined surplus from coarse aggregate production. By using the Internet in search for information of this topic it is evident that a variety of terms are used for this or similar product internationally, including;

- Manufactured stone sand
- Manufactured fine aggregate
- Crushed fine aggregate
- Crusher sand
- Crushed rock sand
- Stone sand
- Stone powder
- Quarry fines
- Quarry sand
- Artificial sand
- Leftover rocks from mining and quarrying
- Surplus materials

In addition different other languages operate with other definitions of manufactured sand.

The term sand refers to relatively small particles; however, there are some variations in the definitions of sand with regard to particle size. According to geological terminology sand is of the particle size 63 µm - 2 mm but in the practical life of aggregate production material ranging from 0/4 mm, 0/8 mm, 0/10 mm and even 0/12 mm is often called sand. In the context of this report, material of the particle size 0/4 mm is referred to as sand and this reflects the common practice.

According to the machinery producer Nordberg (1999)³, now Metso, manufactured sand has been used for many years in a variety of concrete applications including waterway and dam projects, highway and airport paving, bridges, power plants, all types of industrial and commercial construction, and concrete products (pipes, blocks and precast) of all kind. Manufactured sand is also used in plasters and mortars, where sand has a full role as aggregate. Furthermore, sand is used partly in asphalt, road building, earth fillings, bricks, glass etc. Table 1-1 shows aggregates average utilization in the world.

Table 1-1 Common aggregate application and average proportions in the world (Nordberg, 1999)³.

Destination	Proportion
Ready mix concrete (30% sand)	36 %
Mortars	18 %
Pre-cast concrete (25-35% sand)	12 %
Asphalt (35-45%)	9 %
Sub-bases	18 %
Ballast	2 %
Others	5 %

1.3 Principal Properties of Manufactured Sand

The Particle Size Distribution (PSD) curve of manufactured sand is more often than not dense. In an optimal crushing process it is possible to obtain particles which are cubical and angular, but with a rough surface texture. Lithology has not so much impact on geometric properties for the sand fraction, i.e. 63 μm - 4 mm, however it may govern these properties for the fines. The effects of secondary minerals on properties and quality of the fines, for use in for instance concrete, are only partly known.

Properties of aggregates from natural sand and gravel deposits (natural aggregates) differ compared to aggregates from crushed rock (crushed aggregates). Natural aggregates are weathered and their surface is often smooth and particles are sub angular to rounded. Crushed aggregates on the other hand have a rough surface texture, particles are angular and, if the production process is adequate, their shape is cubical. However, with traditional crushing techniques a high content of flaky and/or elongated particles may occur especially in the particle size range < 8mm. This difference in surface texture and shape properties indicates that natural and crushed aggregates are two different types of material and must be treated accordingly, i.e. different requirements apply to the two types, for instance regarding particle size distribution. Knowledge and experience for natural aggregates can for instance not be used without suitable adjustments.



Figure 1-1 Example of natural sand deposit. Particles are in general rounded.



Figure 1-2 Example of crushed, manufactured sand. Particles are in general angular and have broken surfaces

The PSD curve, for manufactured sand normally resembles a Füller curve, i.e. is hanging or dense with high proportions of fines content, opposite to what is normal for natural sand. A dense PSD in concrete sand can reduce the water requirement, and thereby improve workability – given the fines content is not too high. On the other hand, if the particle shape is sharp/flaky, a dense grading may cause a harsh mix, requiring much fines to compensate the voids content – again increasing the water demand. So this is a tight balance to be played with the parameters in each case. Often good results have been obtained with a blend of natural and manufactured sand, in which case an optimised grading curve as well as a mix of rounded and sharp particles can give a better solution than any of the singular alternatives.

The most important elements in the production of manufactured sand are shown in Figure 1-3.

The first and basic issues will be related to the raw material – the inventory, classification and excavating. Material parameters will depend on the parent rock, whether the aggregates are excavated and crushed from hard rock, or they are present as sand/gravel deposits of one kind or the other. Geological parameters such as rock type/mineral composition and texture, weathering, contamination and sediment structure, will always be the initial criteria for selection and evaluation of resources.

The production process, comprising initial transport, crushing, sorting and storage, will then be the decisive stage in providing a useful aggregate. Adequate production equipment and methods, based on the geological conditions given, are key elements in obtaining the necessary results.

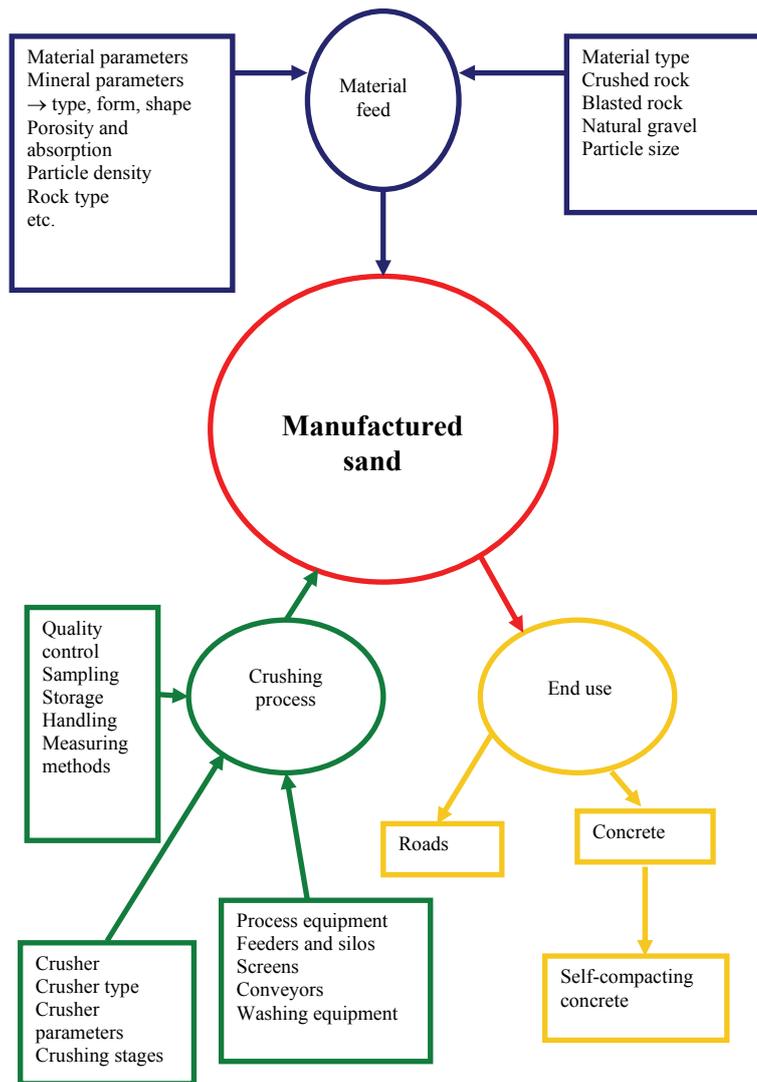


Figure 1-3. Flow chart showing some of the factors affecting quality of manufactured sand.

As manufactured sand often is produced dry, with high fines content, and a “long” grading, segregation is common when storing and transporting manufactured sand. As a consequence it is necessary to define procedures for sampling, handling and testing for quality control purposes to ensure that the “right” material is being tested. Crushers are significant in the final outcome when manufacturing sand, in particular the crusher type, their setting and the number of crushing stages. Other processing equipment includes feeders and silos, screens, conveyor belts and – in some cases – washing equipment.

Finally, it is important to know from the start the intended end-use of the material since the optimal properties vary according to end-use and this may often be controlled during the processing period.

1.3.1 Fines

The definition of particle size of fines is diverse. According to the EN-product standard EN 12620⁴ for concrete aggregates, fines are all material less than 63 μm . ASTM standards have a similar limit of 75 μm . For practical concrete purposes in Norway it is quite common that all material less than or 125 μm are referred to as fines.

While fines is a part of the sand aggregate, either the lower part of the grading curve, or sometimes also as a contamination, the well defined, added fine size fraction is commonly referred to as filler. Commercially fillers are supplied mostly from limestone, sometimes from quartz. But even the bottom size of the actual aggregate can be produced as well defined filler.

2 Prospects of the Future – Environmental Challenges

As it has been mentioned, it is recognised, both nationally and on a global scale, an increased miss balance between the need for aggregates in the society and the availability of traditionally suitable geologic sources. We can estimate that close to 80% of the sand and gravel ever taken out of the nature, has been consumed in our generation. According to prof. Roger Flanagan, UK (lecture given at NTNU Trondheim in October 2008), the availability of materials will be one of the important global market drivers in the years to come. As a consequence there is a strong need for developing and implementing technology that can enable the use of alternative resources, reduce the need for transport and present zero waste concepts for the aggregate and concrete industry.

In Norway it is already the situation, as natural aggregate resources near urban centres terminate, that the transport distances increase significantly. According to information from the Geological Survey of Norway, NGU, (2008)⁵ it is clear that some of the most important natural sand and gravel resources, e.g. in south-western Norway, and areas serving the Oslo region, will be finished within 10-30 years. It has been emphasised by NGU that there is a clear need to develop a strategy how to preserve important concrete aggregate resources, and what to do in regions already scarce in natural aggregates.

In a forecast for the aggregate market in US, presented by Vulcan Materials Company (2007)⁶, it is claimed that the demand for aggregates will continue to grow in the future. The demand will be driven primarily by population growth and the associated requirements for residential and non-residential construction, and the need to upgrade and/or replace aging infrastructure of all types. It is emphasised that it will become more difficult to site and open new quarries, particularly in proximity to high-growth areas. It is also predicted that the need to ship aggregates over greater distances will increase the number of distribution facilities in metropolitan areas. Other issues of consideration in their forecast are:

- The need for aggregate producers to meet tighter specifications, will result in more unusable materials being produced.
- Recycled concrete will continue to play an important role in urban areas; however, recycled materials will remain a small part of the total aggregate supply.
- Community relations issues in the future will remain important and will likely place additional restraints on locating and operating aggregate facilities.

2.1 Sustainability- and Environmental Challenges

In 1989, the Brundtland Commission articulated what has now become a widely accepted definition of sustainability⁷: *"[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 (2000)⁸ 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)^{9,10}. 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 the environmental and sustainability aspects along the entire process line from materials inventory, via production and use, to final area reclamation.

Danielsen (2006)¹¹ presents 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 and concrete 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 natural resources, especially in regions facing a coming shortage of adequate local materials,
- The environmental impact on neighbourhood 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 industrial 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 of material properties may aid 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 more expensive constructions whereas aggregates with lower quality may be selected for massive fills where quality demands are 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.

2.1.1 Environmental impact – Energy and Transportation

In a report by Lagerblad et al. (2008)¹², 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. As a consequence they claim that when introducing manufactured sand it is important to ensure that length of transportation does not increase.

Some figures regarding energy consumption and corresponding CO₂ emission of aggregate production and transport has been compiled for a Norwegian aggregate producer (Hotvedt, 2009)¹³. The figures are based upon some average experience data and some best guesses. As a measurement of energy, the figures of emission of CO₂ 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 CO₂ emission per kWh may be applied.

Table 2-1 presents figures for the production of crushed gravel originated from blasted rock. In Table 2-2, figures for the production of gravel from natural sediments are presented. As evident from the tables, the energy required, in terms of CO₂ emission per ton of aggregate produced is 1.44 times higher for crushed gravel compared to natural gravel.

Table 2-1 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 2-2 Energy consumption - Gravel production from natural sediments

Activity	Energy sources	Consumption		CO ₂ pr unit		Emission CO ₂ (kg CO ₂ /ton)
Production	Diesel oil	0.57	litre/t	2.69	kg/litre diesel	1.53
Production	Electrical power	2.50	kWh/t	0	kg/kwh	0
Total						1.53

Table 2-3 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 a distance of 17.7 km, equals the CO₂ emission per ton of aggregate as for the production of crushed gravel from blasted rock. Corresponding transportation length for production of natural gravel is 12.4 km.

Domestic transportation of aggregates by a 1.000 tons vessel, e.g. 40 km, implicates 0.6 kg CO₂ emission per ton of aggregate. In the case of export of aggregates, e.g. of distances 600 km, the CO₂ emission per ton of aggregate for a 4.000 tons vessel is 10.7 while for a bigger vessel (27.000 tons) the emission is only 3.9.

Table 2-3 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

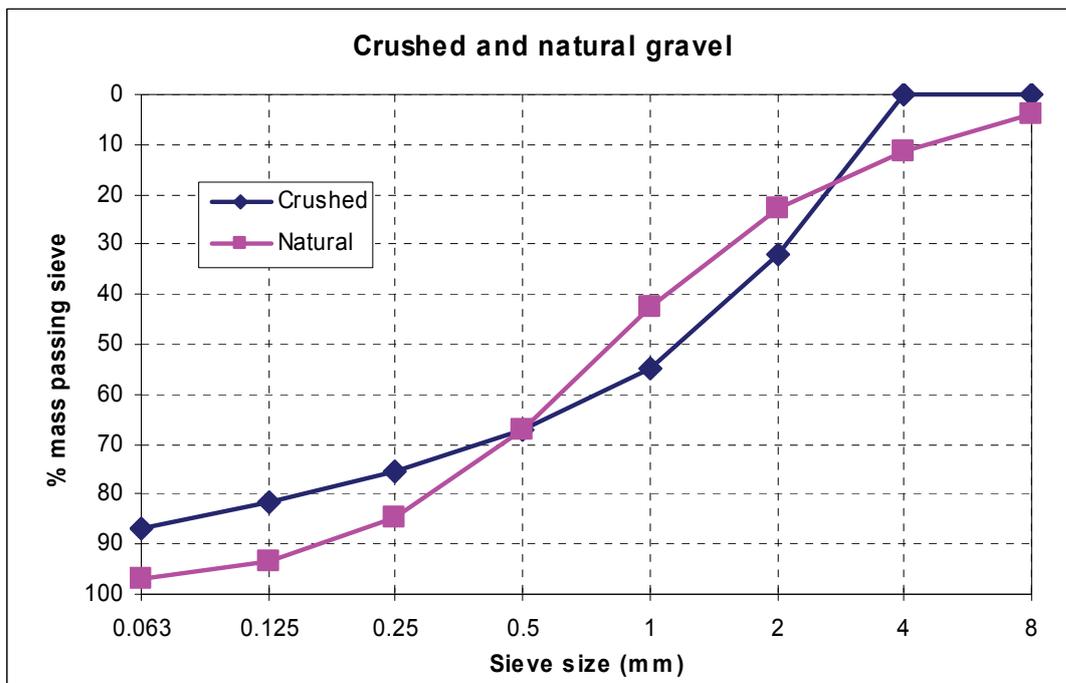
CO₂ pr unit: 2.69 kg/litre diesel

2.2 Technical Challenges

One of the main challenges in aggregate production, especially when producing crushed aggregates from hard rock quarries, is to obtain a satisfactory mass balance. Any excess fraction that has to be kept on stock – or even more; deposited – will create an economic as well as an environmental problem.

The production of crushed aggregates normally gives a miss-balance of particle sizes, as the relative quantity of the sand fraction (0-4 mm) in most cases exceeds what can be placed on the market: Unless special processing precautions are taken, the crushed sand will end up with a more or less uncontrolled fines content, far in excess of what can be tolerated if the end product is concrete. These surplus fines have traditionally been considered a waste material at most plants, and have caused considerable deposition costs for the producers as well as being a problem also from an environmental point of view. Besides, the sharp angular nature of the crushed materials along with a grading curve different from that of natural sand, calls for precautions in the mix design if the potentials of the material shall be taken to benefit.

Figure 2-1 shows some of the principle differences between natural and manufactured sand, (Danielsen & Ørbog, 2000)⁸.



Typical values	Manufactured sand	Natural sand
Grading	packed/dense	open/straight
Filler content (<0,125µm)	10-25%	2-8%
Surface area	2-300.000 m ² /m ³	50-70.000 m ² /m ³
% cubical particles	30-50%	40-95%

Figure 2-1. Manufactured sand characteristics

2.2.1 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 (Danielsen, 1987)¹⁴:

- **Geology** – the geological basis for the materials, whether to be excavated from a sand/gravel pit or quarried in a hard rock deposit.
- **Production technology** – the various equipments 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 2-2 below.

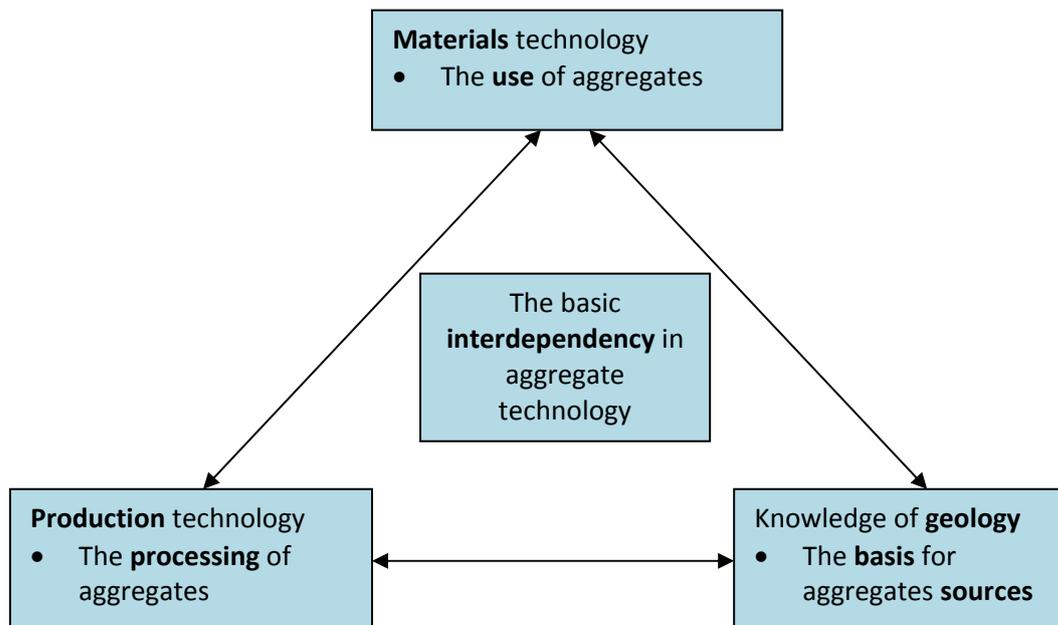


Figure 2-2. Principles of aggregate technology. (Danielsen, 1987)¹⁴

2.3 Economical Challenges and options

As pointed out in the forecast presented by Vulcan Materials Company (2007)⁶, 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. And it will also increase the environmental impact in terms of pollution and energy consumption.

As pointed out by O'Flynn (2000)¹⁵ the major cost component of aggregates as a bulk low-value commodity is transport, and they must be won as close as possible to the urban centres where they are consumed.

In the situation of rapidly depleting sand resources this implies the need for developing useful alternatives, e.g. in the form of crushed/manufactured hard rock, recycling, sub-surface quarrying etc. A change to alternative materials sources will then also necessitate the development of new technologies for the end materials and structures, a part of this being the materials and construction standards.

Economically, reduced transport costs will more or less balance higher cost relating to local quarrying and to a more expensive end product (e.g. higher cement requirements and need for additives in some concretes). Short-travel solutions for aggregates (and not least sub-surface alternatives) also can make the concepts of integrated plants more attractive (quarrying in combination with industrial production of e.g. asphalt and concrete, and with an option of receiving and depositing waste and recyclable materials in the quarried volume).

3 Production and Processing of Manufactured Sand

Manufactured sand has been produced by a variety of crushing equipment, including cone crushers, impact crushers, roll crushers and rod mills. According to the machinery producer Nordberg (1999)³, now Metso, there are many single details affecting the quality of manufactured sand, as presented in Figure 3-1.

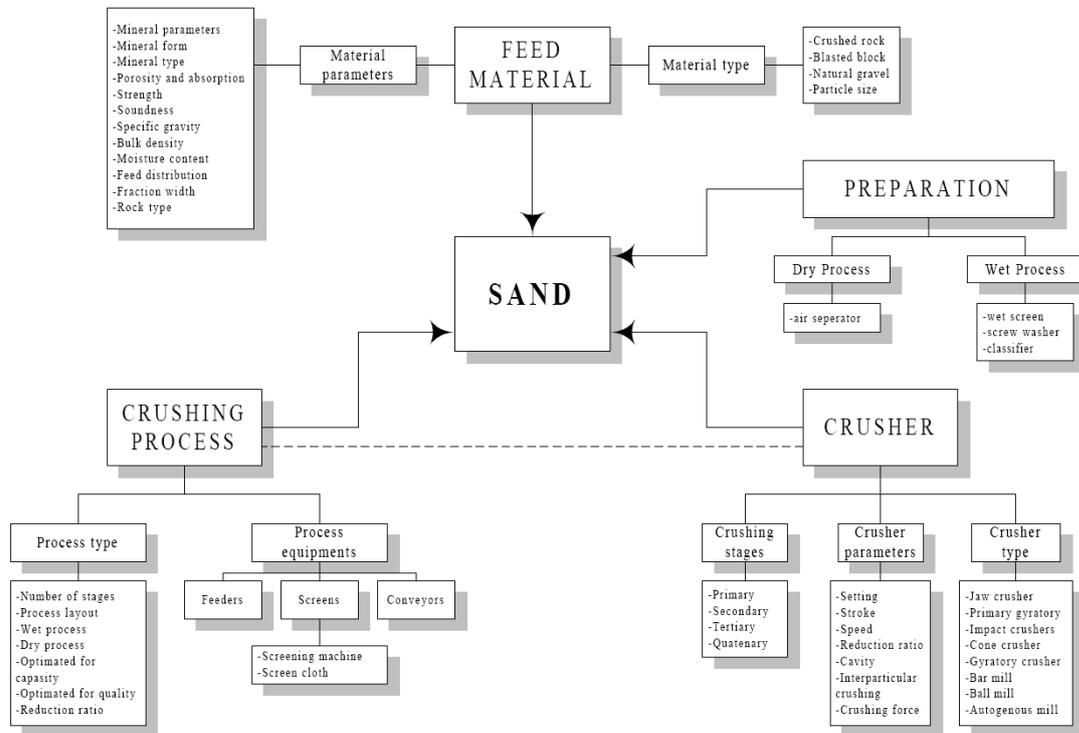


Figure 3-1. Graphic presentation of the factors affecting the quality of manufactured sand (Nordberg, 1999)³.

3.1 Geological, Mineralogical & Petrographic Issues

The raw material for production of manufactured sand is the parent mass of rock. Thus, many aggregate properties depend on the properties of the parent rock (e.g., chemical and mineralogical composition, petrographic classification, texture, surface properties, alterations, specific gravity, hardness, strength, physical and chemical stability, pore structure and colour). All these properties have an important influence, both upon the blasting and crushing of manufactured sand, e.g. energy consumption, fines production and shape, but also upon the quality of fresh and hardened concrete. Mineralogy and petrography can be quantified in order to estimate the quality of aggregates in exploration procedure, and to assess and verify the quality of subsequent test results.

Among the well known relations is the negative influence of free mica for the water requirement in concrete – and also that this is more detrimental for crushed sand than for natural sand, where the surface properties of the mica minerals have been altered during thousands of years’ natural weathering.

Further to the mineral surface properties, studies have shown differences in the response to chemical admixtures between aggregates with different mineral composition, especially

relating to basic versus acidic rocks, carbonates versus silicates. And the way how mineral surfaces influence upon the contact zone aggregate/cement paste has been investigated (Danielsen, 1979)¹⁶ e.g. showing that altered (to zoisite or sericite) feldspars contribute to higher strength than non-altered feldspars.

There is also a well known relation between the texture and mineral composition of the rocks and the size distribution and particle shape of the crushed product. E.g. will the geometrical properties of crushed sand from medium to coarse grained rocks very often be directly a function of the mineral grains composing the rock, while fine grained rocks frequently will produce more flaky/elongated particles of complex composition.

While the mineral composition of sand/gravel will be determined by the different rock types composing the bedrock up-stream of the quarry – and thus can be hard to control – manufactured aggregates can be taken from one single source of rock, with a better chance to keep the composition under control.

In a study by Bohloli and Hoven (2007)¹⁷ laboratory and full-scale studies were carried out to explore the possible relationship between fines production and water content of rock material. A test called the “Brazilian tensile test” was selected for the laboratory study while a cone crusher was employed for the full-scale trials. Results of the laboratory work showed that the percentage of fines fraction produced was a function of the type of rock tested and the tensile strength of individual specimens. For the rocks investigated, a correlation was found between its strength and its fines generation. The influence of water content on production of fines was also examined and showed that increased water content reduces both tensile strength and fines generation in the laboratory. The impact of water content on aggregate production was also studied in full-scale but the results were not as clear as those of the laboratory tests.

In a study by Donza et al. (2002)¹⁸ the influence of the mineralogical source of manufactured sands for production of high-strength concrete was studied using three different types of crushed sands (granite, limestone and dolomite) with similar grading. It was concluded that manufactured sand could be used to produce a high-strength concrete with similar or better mechanical properties than corresponding concrete made with good natural sand. The shape and texture of manufactured sand particles had an important effect on the interlocking of paste and aggregate particles, leading to an improvement of strength of concrete. Manufactured sand produced from granite appears as the most advantageous for this purpose in this study.

Räisänen (2004)¹⁹ investigated the relationships between petrographical and mechanical properties of rock aggregate raw materials in Finland. In the study it is pointed out that the modal composition, mineral shape and grain size distribution, and the amount of fine-grained matrix have an effect on an aggregate's resistance to fragmentation and abrasion. In addition it is emphasised that the spatial dispersion of minerals also has an important effect on the mechanical properties of rocks. The correlation between the mechanical properties and quantitative petrography of rocks is dependent on various petrographical properties simultaneously. Thus, most studies have mainly concentrated on groups of rock or geological property, e.g. Brattli (1992)²⁰ on basic igneous rocks.

Joyce & Joyce (1999)²¹ emphasises the problem occurring when applying some types of parent rock as raw material for manufactured sand, as the proportion and quality of fines could be undesirable. For instance when crushing a metagraywacke to produce manufactured sand, it is in some cases likely to obtain an increased proportion of unwanted sericite that will increase water demand in concrete and decrease strength. An other example is e.g. smectite clays present in basalts. Although tolerable in concrete approaching 20% in coarse

aggregates, smectite is likely to be troublesome in manufactured sands at proportions as low as several percent.

In a comprehensive Swedish study by Lagerblad et. al (2008)¹², the principle of mineralogical properties of rock as raw material for manufactured sand is discussed. It is reported that typical rock types which are suitable for producing manufactured sand are limestone, quartzite and diabase. These types of rock enable production of cubical particles. However, it is reported that the majority of rock types in Sweden, utilised for production of manufactured sand, are of granitic origin. It is claimed that these types of rock typically produce flaky and elongated grains. However this is in contradiction to what is experienced in many other countries, including Norway. Lagerblad also emphasised that when producing fine aggregate particles, the shape of the particles will be governed by the original shape of each individual crystal.

3.2 Extracting and Blasting

The blasting of the rock shall be regarded as the first stage in the production of aggregates. Blasting should consequently be designed as a part of an integrated size reduction process in the process of production of manufactured sand. According to Nielsen (1999)²² 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 together. 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 (1997)²³ emphasises 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.

3.3 Aggregate Crushing

The comminution of rock materials into gradually more fine grained particle sizes by means of different kinds of crushing is the key process in the making of manufactured aggregates. And the adaptation of the crushing process to the actual rock type and to the intended end-use is crucial for the final result to be achieved. This implies the choice of crushers and their combinations, the number of crushing stages, the feeding, gap setting and operation of the individual crushers and, of course, the maintenance. It is important to realise that a good final result depends on each crusher stage being optimised – it is not a good approach to try to repair an insignificantly crushed product by the final crusher stage alone.

A normal crusher set-up will have a primary crusher (usually a jaw or a large gyratory), one or two secondary crushers which will in most cases be cone crushers, in large quarries even a tertiary cone stage may be used. And then as a final (third or fourth) stage for making cubical fine grained particles, a VSI has often been the solution.

The reduction ratio (RR) is a key figure, indicating the ratio between in-going and out-going size. For cubical particle shape a low RR will be the target, as the lowest flakiness will always be obtained at particle size close to the crusher setting. This could however implement a high number of crusher stages, with consequences for economy as well as for the amount of fines produced.

An overview of relevant crushers and crushing lay-outs can be seen on several producers' websites, e.g. www.metsominerals.com.

Apart from this more or less – at least for Norwegian conditions – standard scheme, impact crushers are frequently used especially with weaker/less abrasive rocks, like limestone (and for recycling), and there have also in recent years been some new development of crushing concepts, like e.g. the new Japanese VSI conversion (V70) and the French Rhodax. All these will be briefly covered in the following paragraphs.

When selecting crushers and planning the overall crushing process, several parameters need to be considered:

- Volume to be produced
- Type of material
- Reduction Ratio
- Feed size
- Throughput
- Product size
- Quality and commercial value
- Capital cost
- Power requirements
- Operational- and maintenance costs
- Environmental restrictions
- Geographical location

The shape of aggregate particles is more and more important. During crushing the shape is improved by:

- Crushing in several stages
- Proper operational control
- Reduction ratios - Low Reduction ratio in each stage (3:1 or 4:1)
- Feed distribution
- Choke-feeding
- Closed-side setting - Best shape for particles sized as the minimum crusher opening
- Changing stroke, speed and cavity design

Table 3-1. Classification and properties of various types of crushers (Wigum & Steingrímsson, 1999)²⁴.

	Compression crushers				Impact crushers		
	Jaw crushers	Gyratory crusher		Roll crushers	Swing-hammer crushers	Impact crushers with fixed blow-bars	Vertical shaft impactors
			Cone crushers				
Reduction ratio	4:1 - 6:1	4:1 - 6:1	4:1 - 8:1	3:1	20:1 - 40:1		
Choke feed	suitable	Not suitable					
Suitable for	All strong rock types, not for weak, or sticky rock types	All strong rock types, not for soft or porous rocks with an ability to pack	All strong rock types	Easy crushed or rocks with low abrasion – layered or weak rocks	Rocks with low abrasion, e.g. limestone – not for strong or rock with high quartz content	Easy crushed or rocks with low abrasion	
Energy efficiency and production volume	Low energy consumption – low production volume	High energy consumption. Much higher volume than comparable jaw crusher			High energy efficiency		High energy consumption
Other	Need particular feeder			Possibility of elongated shaped aggregates.	Low investment- and working cost. High maintenance cost.		Good aggregate shape
Crushing stages	1.	1.	2.-3.			all	3.-4.

3.3.1 Traditional Set-up for a Crushing Plant

The well-known, traditional set-up for a crushing plant in an aggregate quarry was initially not purpose designed to make optimal products, but to provide an effective size reduction of the blasted rock, very much based on technology from the ore mines. Especially secondary gyratory crushers in many plants had a tendency of producing extremely flaky materials, which could be hard to repair for the (eventual) tertiary cones.

A modern, well designed and operated three-step, traditional plant can, however – much depending on the rock type – deliver quite satisfactory, clean and cubical products in the sizes above approximately 8 mm. The most critical size range for such a plant is between approximately 2 and 8 mm, where it is extremely difficult to obtain a good, cubical shape. As for the finest fractions, their particle shape will for most rock types be a function first of all of the mineral texture – but the crushing process does not assist to cubicity.

It follows that a traditional plant will not be suited for producing concrete aggregates in the small or medium grain sizes, while it may operate satisfactorily in a market for coarse aggregates, and also for asphalt materials (which allows for flakier, fine aggregates). This is a reason why we see that such plants may obtain a good mass balance for the situations where there is an asphalt plant located in or close to the quarry, while in the opposite case there can be a problem with surplus fines production and deposits.

Figure 3-2 shows a modern and optimised lay-out for a “traditional” quarry (Lierskogen, Franzefoss Pukk AS). Notice that in this lay-out, the size fractions 0/20, 0/60 and 20/120 are taken out before C1, as quarry run. The concept uses a large cone as C2 (to do as much work as possible in an early stage of the process), taking out ballast and other “moderate quality products” before C3. Finally, 4/45 mm is being fed into two parallel cones as C3, to be produced as the final aggregate product. This concept will produce good quality aggregates for asphalt and concrete down to approximately 8 mm (but does not control cubicity below that size).

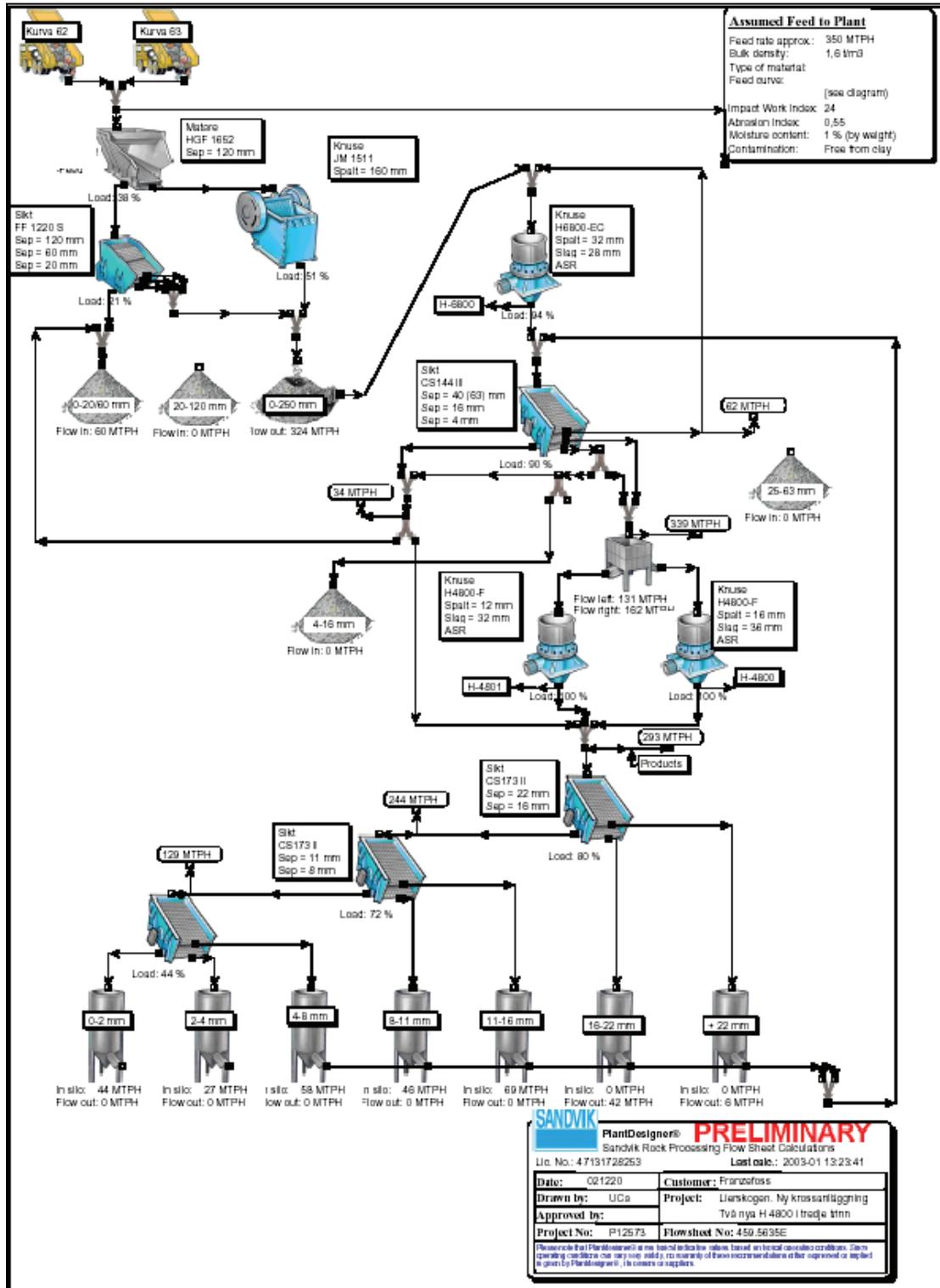


Figure 3-2 An optimised, “traditional” quarry lay-out (Lierskogen, Franzefoss)

A quarry set-up in the “traditional” way as used in Norway could then be:

1. Primary crushing (Feed size: 300-2000 mm), - preparation for next stage.
2. Secondary crushing: (Feed size: 50-400 mm, < 40 mm) - middle stage, potential final stage in smaller operation/gravel.
3. Tertiary crushing: (Feed size: 0-100 mm) - reduction ratio small – focus on shape. Entire major aggregate requirement < 20mm
4. Quaternary crushing: Cubical Manufactured Sand.

3.3.2 Primary Crushers

The first step of crushing is mostly done by large jaw crushers or sometimes also large gyrators. Literature and details can be found in text books, e.g. Smith & Collis (1993)²⁵ “Aggregates” and producers’ websites, e.g. www.metsominerals.com. The primary step is not the most decisive for the quality of crushed concrete aggregates.

3.3.3 Cone Crushers

The cone crusher can be said to be the most determinant factor in the process, doing the volume of the reduction work in most quarries. The choice and operation of cone crusher(s) in a quarry is also (for a “traditional” quarry design) the key to materials quality. In order to start making optimised products in an early part of the process, some modern quarries are using large cones already as C2 in stead of the more flake producing gyrators.

There has been a significant development regarding cone crushers during the last decades, and modern cones in a 3rd step, sometimes two in a parallel with different feed and gap setting, are able to produce excellent and cubical aggregates in the sizes > approx 8 mm, with very optimised flow charts and operation even down to approx 5 mm.

The gap setting and the feed into the cone are determinant parameters for the product outcome.

3.3.4 Vertical Shaft Impactors (VSI)

The installation of Vertical Shaft Impactors (VSI), often as C4, has proved to be an effective way of producing cubical (even rounded) particles in the small and medium size fractions (< approx 5 mm). Delivering aggregates with extremely low flakiness, these crushers (trade names e.g. Rotopactors, Duopactors, Barmac) became very popular in the eighties and nineties, and were installed in several plants. A problem was, however, that these crushers often were put in to repair, in the last step, an aggregate, which was already unsatisfactorily produced in the previous steps. So a consequence of obtaining a cubical shape was the generating of a high percentage of the (often unwanted) 0/4 mm fraction, and a very high fines content in this sand fraction, which appeared partly as a high filler content in the grading curve, partly (and even worse) as a thick fines coating on the coarser aggregate particles. Some characteristic figures:

- Improves particle shape by some 10 – 30%
- Produces >> 30% below 4 mm
- Increases the fines content (< 0.125 mm) relatively with up to 50 %

Figure 3-3 shows an example of grading curves (0-4 mm), as influenced by the rotational speed of a rotopactor (varying 42 to 55 r/s).

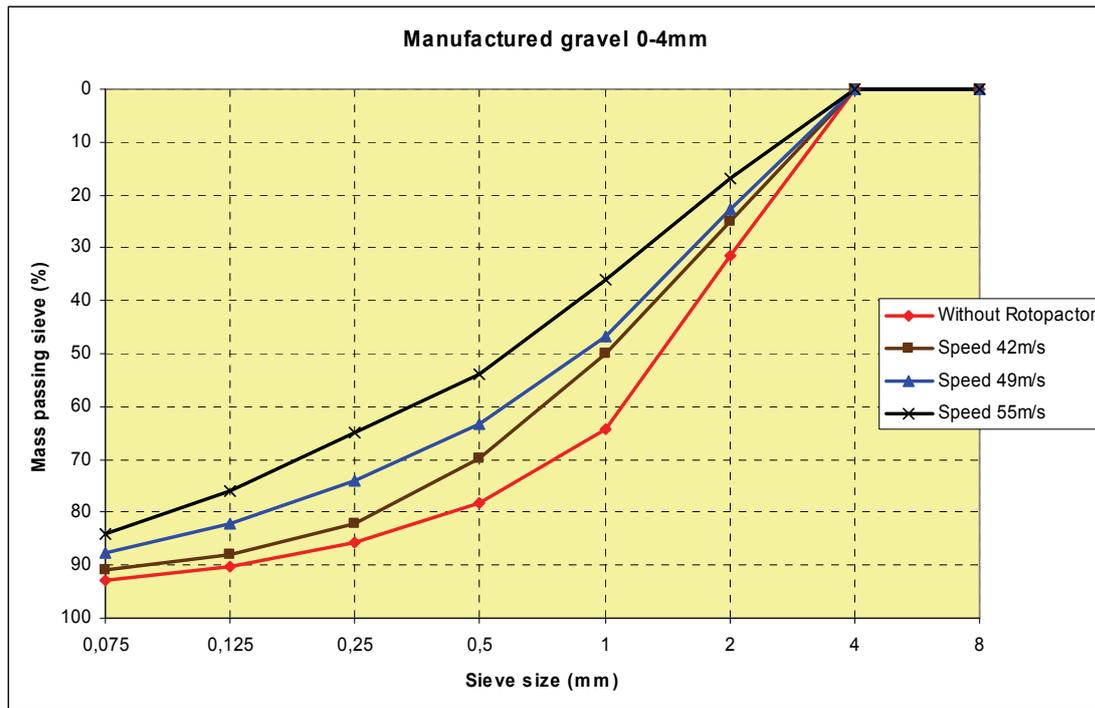


Figure 3-3 Grading curves and fines production as function of rotational speed of rotopactor

Consequently, the disadvantage of a more cubical aggregate was inferior mass balance, a filler content that made an effective concrete proportioning difficult, and finally a coating on the coarse aggregate particles that called for washing in order to keep up the market.

In the conclusions in a study by Powell (2000)²⁶ it was shown that:

1. A vertical impact crusher is capable of producing/reshaping fine aggregates for use as manufactured sand for concrete.
2. The generation of fines is related to mineralogy, feed size, grading and rotor speed.
3. The finer the feed size, the smaller the increase of minus 75- μ m material in the product.
4. Increasing rotor speeds tend to reduce the Uncompacted Voids of the fine aggregate product.
5. Increasing rotor speeds tend to increase the generation of minus 75- μ m material.

During recent years, the design and implementation of VSIs have been further developed. A key to success is that the VSI is given a limited part of the job – not to contribute significantly to the size reduction, but to specifically improve the particle shape of the medium to fine grained product after an optimised cone crushing process. Thus the fines production can be limited and the fines coating on coarse particles avoided. Another key to success is the combination of this procedure with a purpose designed wind sieving equipment, in order to reduce the total fines content in the sand aggregate, and isolate these fines as a potentially commercial filler (to be described later).

Details of modern VSIs can be found e.g. on the websites of Metso Minerals and Sandvik.

In Japan, Kotobuki Engineering & Manufacturing Co. Ltd. (Kemco) has developed existing autogenous VSI technology, by incorporating a milling function, using tungsten carbide impact members a restriction on the crushing chamber outlet, thus forcing the material into a zone of powerful attrition (Pettingell, 2008)²⁷. In the concept known as US7, the particles collide with the tungsten carbide hammers, effective breakage replaces mere abrasion, and

the peripheral speed of the rotor can be somewhat reduced. The second important stage in the process, termed V7 sand manufacturing plant, is the use of air screen – described later in this chapter. This feature allows the US7 crusher to produce the necessary amount of 150µm-1mm grains for an ideal particle size distribution.

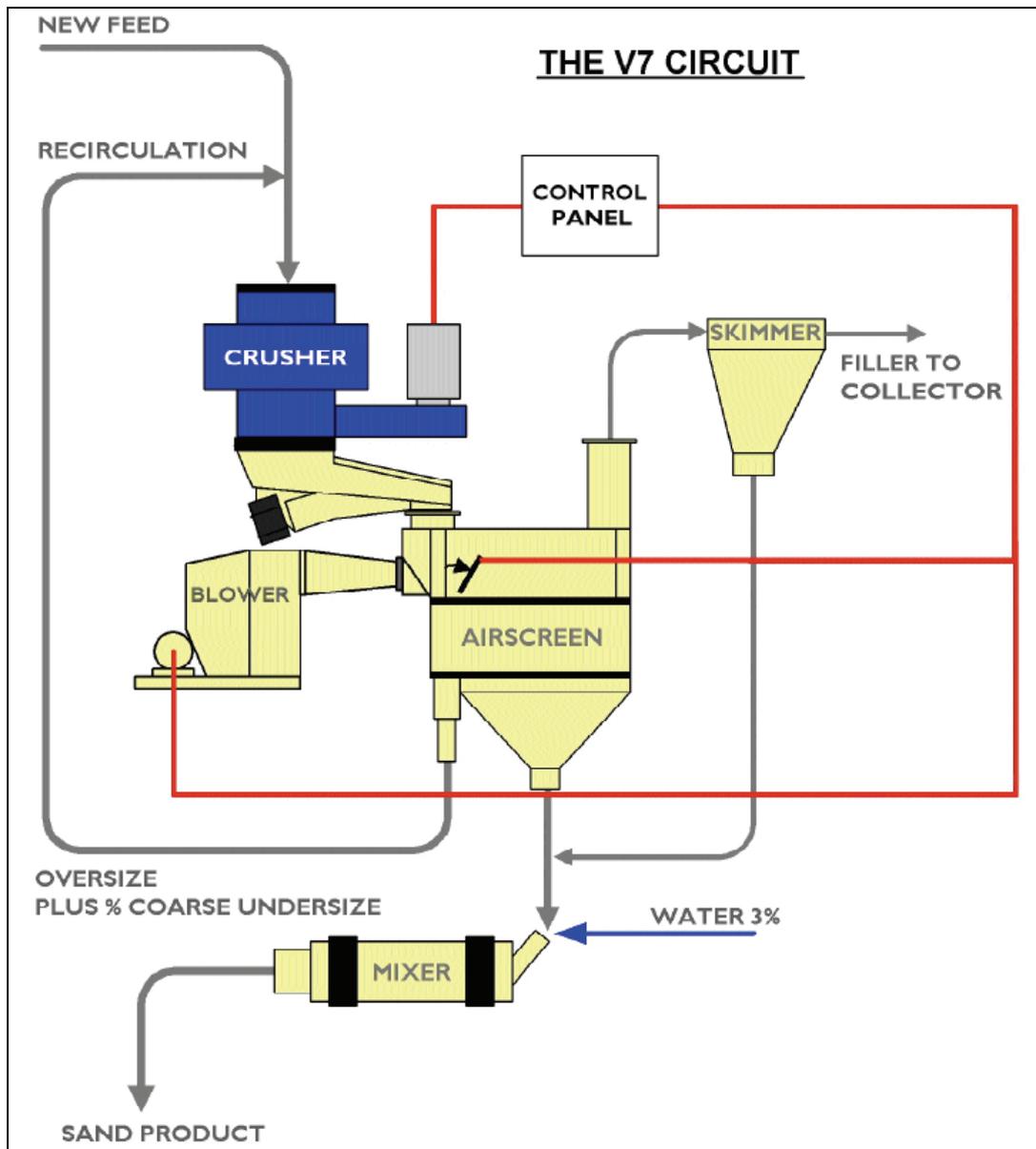


Figure 3-4: The V7 sand manufacturing plant (Pettingell, 2008)²⁷

3.3.5 Impact Crusher

A cubically shaped aggregate can be obtained using an impact crusher, which is mostly used in step 3, parallel with or as an alternative to a cone crusher. Traditionally, impact crushers have been used successfully with soft rocks (e.g. limestone) and for recycling purpose, where they even may serve as a step 2 or as the sole crusher in the plant. They are known to be efficient, and to give good products. The disadvantage is a larger dependency on operator skill and follow-up, and most of all; a high mechanical wear – for which reason these crushers have not been extensively used with hard rock.

The aggregate producer Franzefoss in Norway installed an impact crusher (SBM) in a gneiss quarry in order to improve particle shape as well as mass balance. The result was a

substantial improvement of particle shape for the size fractions > 6 mm compared to the previous cone crusher solution. With the present rock, the mechanical wear was rather high – as was expected. However, the wearing costs appeared to be of an order that questioned the economical feasibility versus alternative solutions.

As for the fine aggregates, there was a slight increase in fines content, but far from the figures experienced for the vertical shaft impactors. On the other hand, there seemed to be a tendency of this crushing mechanism producing a somewhat higher content of free mica in the fine size fractions, than a traditional cone crusher.

3.3.6 Rhodax Crusher

A recent step in crusher development for aggregate production is the use of the French Rhodax. This is a crusher concept which was initially developed for industry purpose (slag, minerals) and which has lately been redeveloped to be adapted for aggregate quarries. As per to day, this kind of crusher has been operating in only few aggregate quarries worldwide, one being in France (Lafarge) and one in Norway (Franzefoss). In the latter case the Rhodax was given up due to high operating cost/low operating availability with the very rigid rock – although the product quality in itself appeared to be extremely good. The Rhodax may be categorized as a vibrating grinder, more than a cone crusher. Its operating principle is quite different from the traditional cone crushers, resulting in more inter-particular crushing. A result of this was that for the first time it was possible to combine a very cubical particle shape, even in the critical intermediate size fractions, with a modest content of fine grained materials (e.g. minus 4 mm).

Figure 3-5 illustrates the operating principle of a Rhodax crusher (FCB Ciment, 2003)²⁸.

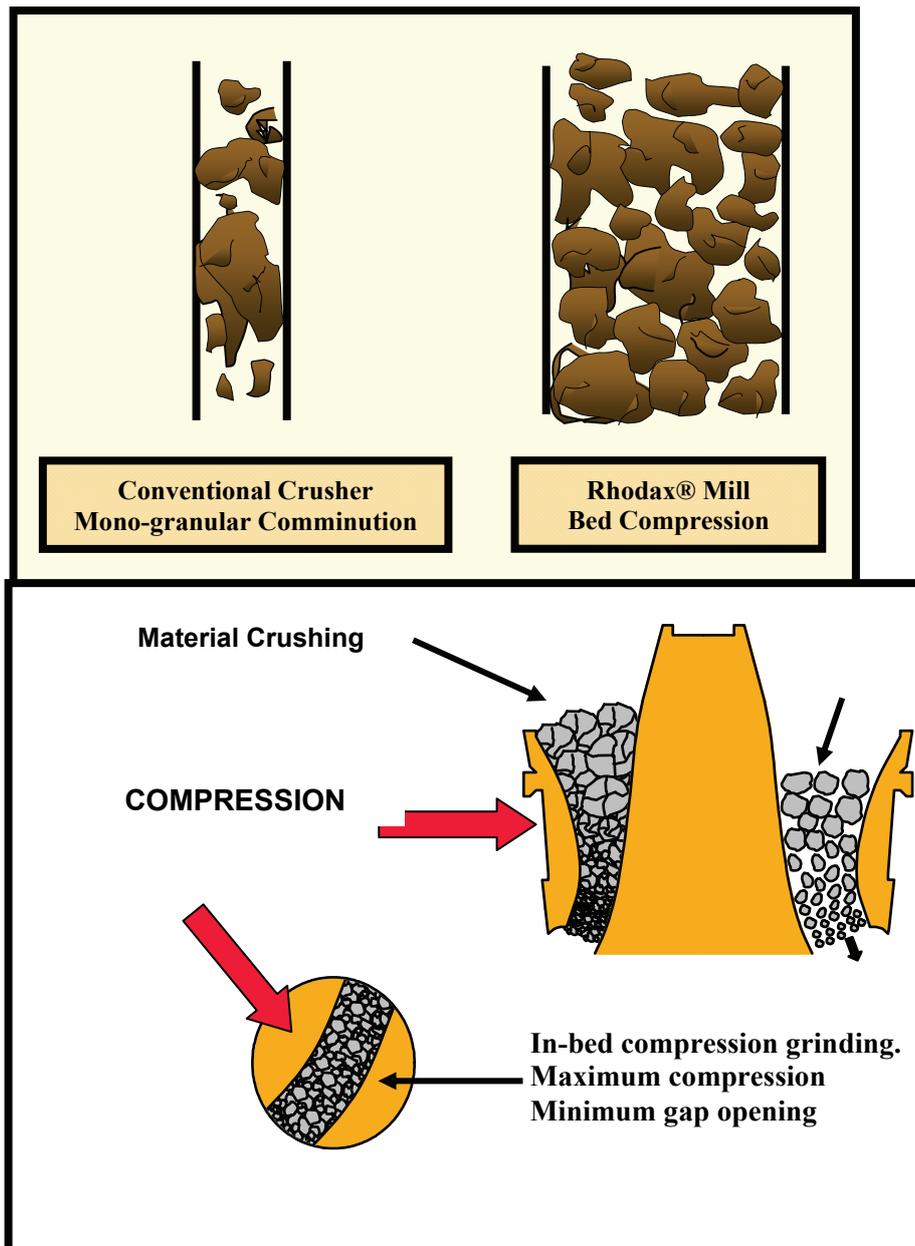


Figure 3-5. Operating principle for Rhodax crusher²⁸

Franzefoss did a pioneering (and expensive) development with this kind of crusher, in close cooperation with the French supplier, FCB Ciment, before having to give it up. Challenges were related to several mechanical details determining the reliability of the equipment, internal materials logistics involving re-circulation of load and feeding of the crusher, and several complicated issues in regulating gap, speed and torque in order to obtain the intended production efficiency along with the product quality expected.

The concept in the actual quarry was to let the Rhodax work in step 3, replacing three other crushers (two parallel cones and one rotapactor) – with at least the same throughput capacity and a better materials quality and mass balance. Probably this crusher concept can, based on very well developed theories, be one of the ways to improve aggregate production in the future. But based on the above experience, this will still call for a significant development e.g. on the mechanical side, in order to ensure reliability.

3.4 Sorting

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/classifying aggregates is available in several text books, e.g. Smith & Collis (1993)²⁵ – “Aggregates”. Specifications for modern equipment will further be available on producers’ websites, e.g. www.metsominerals.com.

This chapter will not present all relevant methods on the market, but rather evaluate which equipment and methods that have been considered especially suitable for manufactured (crushed) aggregates. Some presumptions concerning this kind of aggregate (in contradiction to natural sand aggregates) should then be the starting point:

Presumption	Consequence
Manufactured aggregates are normally more sharp angular, often also flaky, than sand/gravel	This normally calls for higher sieving capacity; larger sieves, elongated sieves, vibrating equipment. E.g. the so-called “flip-flow” sieves like the Trisomat have been successful down to a certain particle size
The crushing process provides a significantly higher content of the finest sand size fractions, also incorporating a high fines content	Challenges with dust. Comparably a higher capacity for fine particle sizing will be required compared with natural sand. Can be a problem with segregation
The grading curve out of crushers is more dense than for water deposited materials	Calls for a different design of the process regarding capacity
Crushed aggregates are dry	Can be a dust problem, should be aware of segregation. The way of storing and homogenising – and also keeping an optimum moisture content (approx +/- 1.5 %) should be aimed at to avoid clogging and segregation
Hard rock quarries are most often located geographically in a way as to prohibit excessive use of water in the classifying (both due to water supply and to depositing and de-watering), in countries like Norway problems connected with winter conditions come as a supplement	Water based classification as well as wet sieving should in many cases be avoided, no matter how successful with natural sand in river or lake areas. Modern wind sieving technology has proved efficient to handle the fine size fractions and the fines content

While wet processing – wet screening, sand screws, classifying tanks, hydraulic classifying – for decades has been the state-of-the-art methodology for washing and sizing natural sand aggregates, this has (table above) not been considered equally suitable for aggregate manufacturing from hard rocks quarries. Being developed first of all for conditions with ample supply of water and run-off conditions, wet processing will have several down-sides in a hard-rock situation, due to both economical and environmental reasons.

In the further development of manufactured aggregate production and technology, the wet processing alternative has therefore to a large degree been set aside and replaced with novel technology based on dry processing – the latest generation of dry screening equipment combined with the latest development of air classifying. For this reason, wet processing will not be covered in this report, and focus will be on the dry processing alternatives.

Sand could be screened in various conditions; wet, moist or dry. As shown by machinery producer Nordberg (1999)³, now Metso, screening efficiency depends on various configurations of the screens and the moisture of the feed.

Table 3-2. Effect of screening parameters and moisture on fine material efficiency (Nordberg, 1999)³.

	Effect on	
	Screening efficiency of fine material	Feeding capacity
Increased rotation speed	++	+
Increased stroke length	-	++
Increased stroke angle	+	-
Increased inclination	-	++
MOISTURE	-	

++ very favourable effect

+ favourable effect

- unfavourable effect

Trisomat screening has been applied successfully in cases where screen hole size is very small or where there the material is particularly damp or sticky or where other less vigorous methods of screening have not been successful. The Trisomat screen (Figure 3-6) uses an eccentric shaft to generate movement of the main frames, inside which are installed flexible but durable mesh screening panels. These screen panels are continuously pulled taut and then are relaxed, causing the material being screened to be vigorously tumbled and to "flip-flop" it's way down the screen towards the outfeed end.

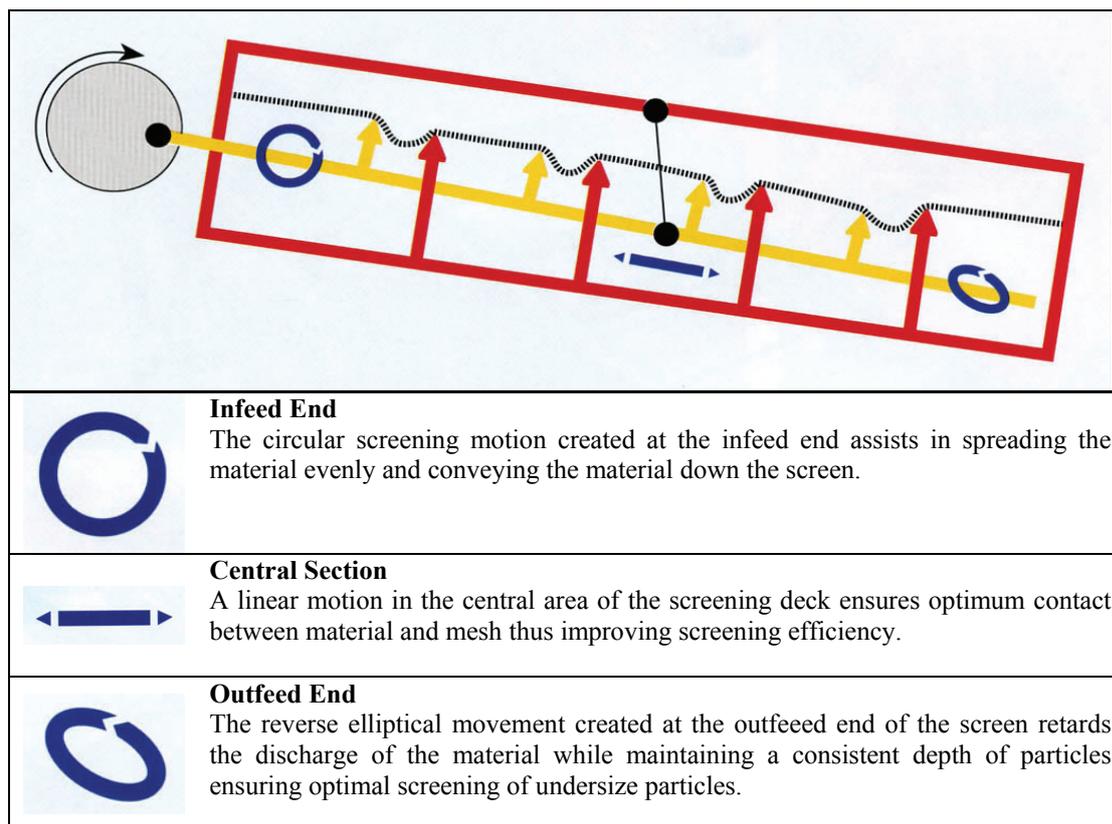


Figure 3-6. Operating principle for Trisomat screen¹.

¹ See e.g.: www.fujikogyo.co.jp/HP-English/triso/triso.html

3.5 Air Classifying

As pointed out by Goldsworthy²⁹, traditionally removing filler has been done by wet classifying, but this has been at substantial cost to the quarry operator. Dry processing is now developing into a cost effective and value-adding alternative. The move away from wet classification has been driven by the need to reduce operation and maintenance costs associated with these activities. Sourcing of water to operate these plants is becoming increasingly difficult. The treatment and reclamation costs of sedimentation ponds have been an expensive but necessary activity. By reducing these costs operators can reduce site costs. 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 customer's are doing, treating this material and selling it in new and exciting industry applications. To handle these materials, innovative operators are turning to a different style of plant design. Previous plant design has been to produce aggregate to stockpile. There have long been issues with stockpiling and aggregate quality. New methods are allowing aggregates to report to silos, which maintains the integrity of aggregate and allows for precise control over the production of concrete and asphalt. This reduces the defect rate. The upside for moving to these systems is two fold. Firstly, inventory control is controlled. Surplus aggregates can be reprocessed at minimal handling cost. Secondly, there is the opportunity to produce a range of speciality products that attract a premium sale price.

One of the manufacturers of air classification is Buell. In November 2007 it was announced that Metso Minerals and Buell, a division of Fisher-Klosterman, Inc, USA, had signed an agreement for the sale of Buell air classification equipment in Europe, Middle-East and Africa (on an exclusive base) and Asia. For Metso Minerals' crushing and screening processes, Buell air classification products offer a cost effective process solution for removing -0.075 mm filler from manufactured sand. Buell equipment is available both for stationary and mobile crushing and screening processes.

The Buell Aggregate Classifiers (Figure 3-7; left) combine gravitational, inertial, centrifugal and aerodynamic forces to efficiently classify materials at cut points ranging from 300 to 75 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 that are 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. Those particles that are near cut point in size are diverted by the secondary air stream into an eddy current within the heart-shaped chamber. Some fines are captured as they enter the unit while others are drawn from the eddy. These are carried by the exiting air to a fabric filter for final recovery.

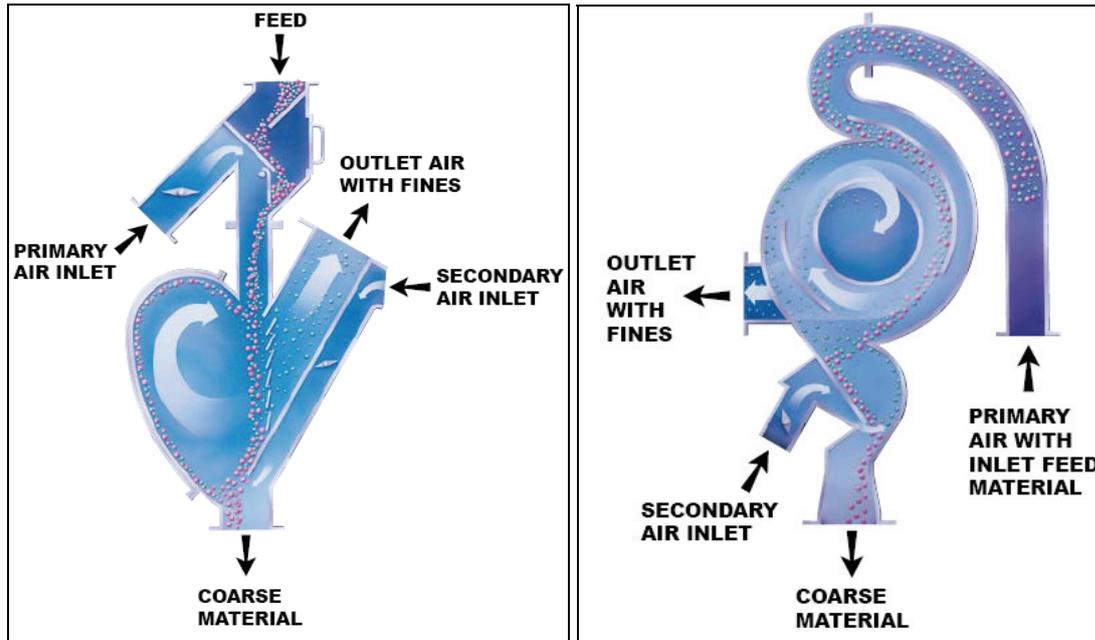
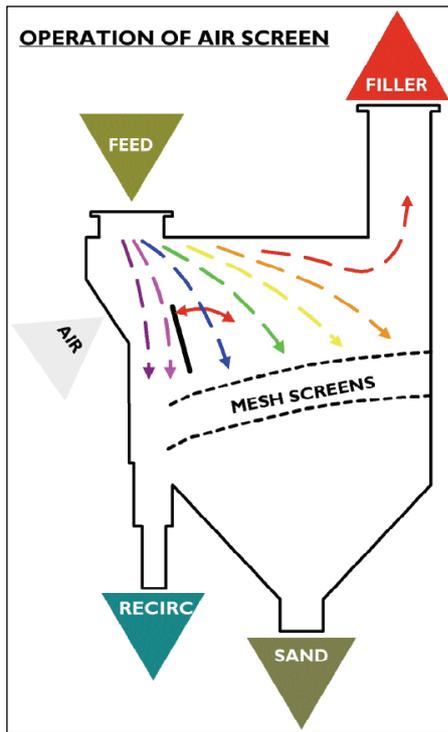


Figure 3-7. The Buell Aggregate Classifier and the Buell centrifugal classifier².

The Buell centrifugal classifier units (Figure 3-7; 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.

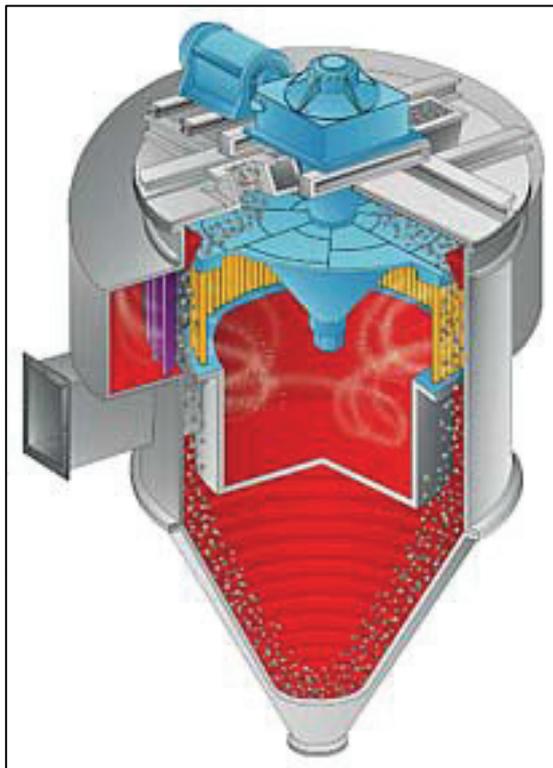
² From: www.buellclassifiers.com/product_powders.htm



In the Japanese concept known as US7 (Pettingell 2008)²⁷, as previously described in Chapter 3.3.4, an air screen was designed using a draught of air as a classification medium, allowing larger particles to fall first and be recirculated, and successively finer materials to drop further along the screen chamber.

Figure 3-8. Air screen operation (Pettingell, 2008)²⁷

Sturtevant Inc.'s Whirlwind Air Classifiers³ uses an internal fan and rejecter blade classification system. 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 3-9. The SDT Classifier for the consistent separation of particles in the 0.152 to 0.037 mm range.

³ www.sturtevantinc.com/airclassifiers.php

3.6 Storage and Handling

According to Dukatz (1996)³⁰ the aggregate reaches the most critical part of the production process, when it is handled and stored. When handling and storing aggregate, it is of great important to take into consideration the following issues:

- Contamination
- Degradation
- Segregation
- Moisture Content

Aggregates are generally stored in open stockpiles on the ground or in silos or bins above or below the ground. Regardless of the storage method, it is very important to keep in mind the four issues listed above. **Stockpiling** of aggregates is the most common and easiest way of storing aggregate. However, stockpiles take up a lot of land, and in small operations, the stockpiles might represent half of the total land base. In tight urban areas, stockpiles may be the most significant visual feature of an aggregate operation. Consequently the large footprint of stockpiles will have a great negative environmental impact. The storage- **silos or bins** can be square or circular. However, According to Dean Frank (2005)³¹, it is very important that their bottoms slope not less than 50 degrees from horizontal on all directions toward a center outlet. In square storage silos and bins, flat bottoms and angular corners should be avoided. Rounded corners should preferable be used, ensuring that all material moves toward the outlet. It should be planned to keep the storage silos and bins as full as practical in order to minimize possible changes in the gradation caused by withdrawal of the material and by breakage of the aggregate particles. In cold climates, the preferred method of storage is in covered overhead or underground bins. In many cases, plants must use heaters to maintain a reasonable aggregate temperature and prevent freezing.

Contamination

According to Dean Frank (2005)³¹, possible sources of contamination include:

- Allowing adjacent aggregate stockpiles to overlap, causing cross-contamination
- Scooping up underlying soil when using a front-end loader to move aggregate from a stockpile
- Dumping the wrong size aggregate in a bin or pile
- Aggregate leakage through or around bulkheads in storage bins
- Allowing leaves and other contaminants to fall into the aggregate stockpile
- Allowing vegetation to grow in the aggregate stockpile
- Failure to let the receiving hopper and conveyor belt or elevator run until empty before adding a different size aggregate
- The supplier may have contaminated the aggregate or delivered the wrong aggregate

Degradation

Experiences have shown that driving by trucks and loaders on aggregate stockpiles might cause enhancement of fines and dirt because their weight can break the aggregate particles and track mud and dirt into the piles. In some cases, e.g. storage close to the sea, it may be necessary to cover the storage area to prevent contamination.

Segregation

Segregation of aggregate is the separation of the course particles from the fine particles. Aggregates with a wide range of particle sizes tend to be most susceptible to segregation. It is important to handle and store aggregate by methods that minimizes segregation.

Aggregates should not be stored in large conical piles, since there is a potential for the course aggregate to roll out and separate from the smaller particles. It is better to store aggregate in small piles or in horizontal layers as there will be less tendency to segregate. In addition, the

type of aggregate has an effect on the probability of segregation. Crushed aggregate is less likely to segregate than rounded aggregate.

If aggregate is dropped from conveyor, some of the fine material may be blown aside, causing a segregation of fines on the lee side of the pile. When a silo or bin is being filled, the material should be dropped from a point directly over the outlet. Material slid in at an angle or material discharged against the side of a bin will segregate. Since a long drop will cause both segregation and the breakage of aggregate particles, the length of a drop into a bin should be minimized by keeping the bin as full as possible at all times. When discharging aggregate into bins, it should be done from directly above and onto the centre of the pile. Discharging aggregate against the side of a bin or a baffle will tend to cause segregation.

Moisture content

Controlling moisture in aggregate stock is important, both due to the fact that the concrete producer wants to receive materials with uniform moisture content, and due to the fact that damp sand has a less tendency to segregate. In the process of the Japanese US7 concept (Pettingell 2008)²⁷ it is usual to condition the finished sand with a small percentage of water (3%), in a small drum mixer, to prevent segregation and maintain consistency.

4 Characterisation and Testing

At the COIN Workshop in Stavanger¹, representatives from Metso Minerals emphasised that they would like to see development of test methods for fine aggregate. As an equipment and solutions provider, they regarded it important to know more about the exact shape and gradation requirements of end users/concrete producers, so that the right equipment recommendation can be made to the aggregate producer.

4.1 Test Methods

There are many various test methods presented in order to classify the various properties of manufactured aggregates and fines. In various parts of the world, various standard methods are introduced, e.g. the American Standards (ASTM) or the European Standards (EN). In addition various countries have introduced their own standard methods, or methods are introduced by scientists for specific purposes. It is not the purpose of this report to make an overall review of all the various methods applied, but exhibit some experiences of the various methods in order to classify manufactured sand and fines for use as concrete aggregate.

4.1.1 Characterisation of Rock as Raw Material

Petrographic description is a technique to express the mineral content of an aggregate. The European Committee for Standardization, (1996)³² has issued the EN 932-3 test for general properties of aggregates. However, as emphasised by Lagerblad et al. (2008)¹², when examining the properties of a rock for use in production of manufactured sand, it is also important to consider the texture of the rock and put into context of what kind of crusher equipments are going to be used. They suggest extending the petrographic description to also address these issues, including measurements of crystal grain sizes.

4.1.2 Characterisation and Testing of Sand and Fines

Hudson (2000)³³ pointed out that one of the problems in dealing with manufactured sands is the lack of a set of tests that fully characterize the three main properties of the individual particles. The properties, according to Hudson, that should be characterized are:

- particle shape,
- particle size,
- particle surface texture.

Hudson claims that not only is it a necessity to know these individual properties of the aggregates, it is also important to know how these properties influence the concrete in both its hardened and plastic states. It is also desirable to understand how the properties of each of the aggregate sizes, or material types, impacts on the entire aggregate blend.

In a paper presented by Rogers & Gorman (2008)³⁴, the development of a test for measuring the amount of flaky particles in fine aggregate is described. Commercially available slotted sieves for testing grain or seeds are used. Material in the pass 4.75 mm to 2.36 mm fraction is tested on a 1.8 mm slotted sieve and material in the pass 2.36 mm to 1.18 mm fraction is tested on a 1.0 mm slotted sieve. The equipment is inexpensive and the test is not excessively time consuming. According to the authors, there is a need to gain experience with this test in a variety of laboratories and applications. It is thought that this test would never be suitable in a material specification. It might be used by people selecting sources of material, as a screening test, to indicate potential problems related to excessive amounts of

flaky particles. It can also be used to compare the effect of different crushers and crusher systems on generation of flaky particles in fine aggregate.

Rogers (2008)³⁵ has emphasised that the measurement of the bulk relative density (specific gravity) of manufactured sands and crusher screenings using e.g. the ASTM C 128³⁶ or EN 1097-7³⁷ test methods, may be in error when high fines ($- 75 \mu\text{m}$) are present in the sample. These differences in density can be large and can result in errors in calculating concrete and asphalt mixture characteristics. Sands with high fines content give abnormally high absorption and low bulk relative density values. This is caused by the fines promoting the formation of agglomerations of artificial aggregate particles as the sample is being stirred during the achievement of the saturated surface dry condition. These artificial aggregate particles have porosity in and of themselves and reach a saturated surface dry condition. The porosity (absorption) and bulk relative density measured is a combination of not only the individual grains in the fine aggregate but also of the artificial particles. A warning about this phenomenon has been placed in the ASTM and Canadian test methods.

To evaluate a sand or a blend of sand in New Zealand, the NZ Flow Cone test (1986)³⁸ is used to measure flow and void properties (Goldsworthy)³⁹. It is widely used within New Zealand and has also been adopted in other countries for characterisation of sand aggregates, e.g. at SINTEF in Norway. A version of the test has also been introduced as a ASTM standard⁴⁰. The test involves passing a determined mass of sand through a cone into a receiver. The time taken for the sand to pass is recorded. In addition the loose density of the sand after passing through the cone is measured. The flow time of a sand is a function of grading, particle shape and texture. According to Goldsworthy, experience has shown that this test provides a very good starting point for determining the performance of fine aggregate.

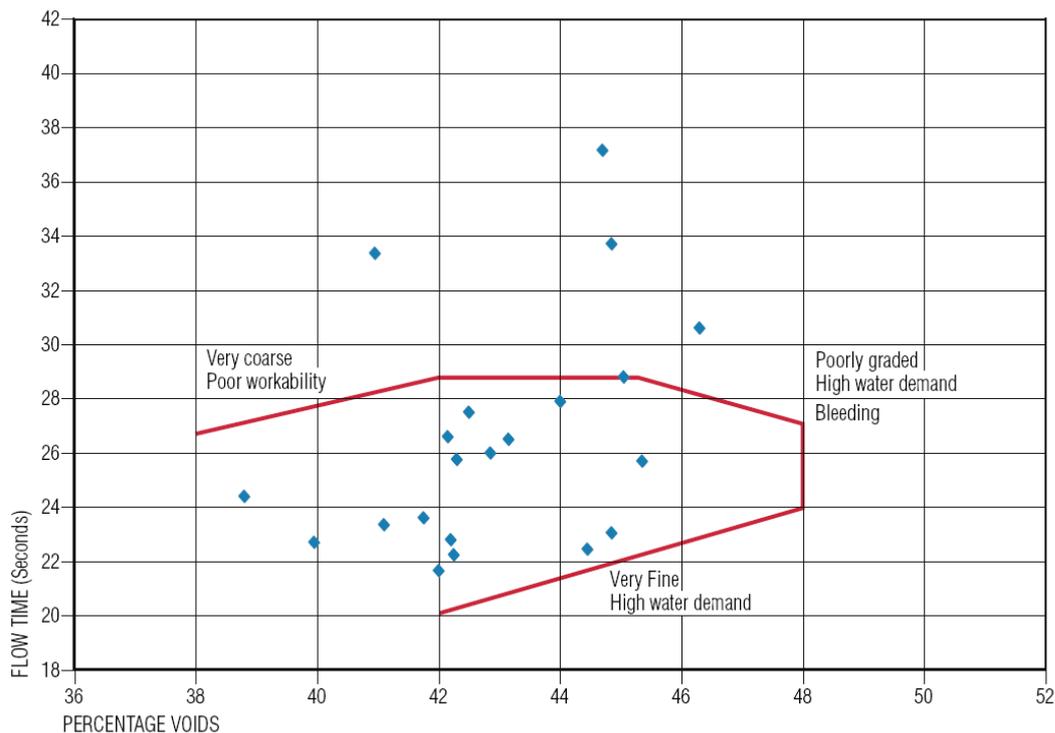


Figure 4-1. The red line differentiates the sands that are suitable and non suitable to be used in normal concretes. Dots lying outside the line are considered unsuitable because; they produced harsh concrete or their water demand was excessive (Cement, Concrete & Aggregates – Australia, 2007)⁴¹.

A new method was developed by Fung et al. (2008)⁴² which measures the packing density of fine aggregate under wet condition. It is called the wet packing method and has the advantages that it is less sensitive to the amount of compaction applied, and that it includes

the effect of water. The wet packing method has been compared to the dry packing method by applying both methods to measure the packing density of crushed rock fine aggregate. It was found that the packing density of crushed rock fine aggregate could be 24% higher under wet condition than under dry condition and that the addition of superplasticizer could have a marginal contributing effect. Furthermore, it was demonstrated that the beneficial effect of blending different size aggregates together is better revealed by the wet packing method than by the dry packing method.

The Texas Transportation Institute and Texas A&M University System carried out a study in 2001 (Zollinger & Shondeep, 2001)⁴³. They pointed out the lack of proper definition, and knowledge regarding nature, and characteristics of different aggregate fines, their properties, and effects on Portland cement concrete. The focus of this project was to examine the methods and test procedures used in the past to characterize the properties of fines, and develop, on a preliminary basis, a framework to characterize and catalogue the properties of aggregate fines, propose new ones that would eventually complement a set of guidelines for the use of aggregate fines in Portland cement concrete. A test run of this classification process is provided as a demonstration of its utility to distinguish aggregate fines possessing different properties and characteristics. Possible applications of aggregate fines, such as in high-performance concrete, controlled low strength materials, were discussed as future directions of research.

A subsequent study was carried out by the International Center for Aggregates Research and the University of Texas at Austin in the period from 2003 – 2005 (Stewart et. Al, 2006)⁴⁴. The task was to identify the characteristics of fines that govern their effects on concrete performance, based upon the fact that the current ASTM C 33 (ASTM 2008)⁴⁵ specification limits the amount of aggregates smaller than the 75 µm that can be included in concrete mixes to 3–7%. Fourteen aggregates were collected for evaluation in this study. Methods of characterizing the microfines to determine their effects on concrete properties were developed. In addition to fully characterizing the aggregates using advanced techniques, simple tests for microfines that could be used as a criterion for their exclusion or inclusion were evaluated. It was stated in the study, that for such a test to be meaningful there must be a strong correlation between its results and concrete performance. Mortar and concrete mixes incorporating microfines from fourteen different aggregates were tested in this project for a variety of performance criteria. This project fully characterizes microfines and evaluates simple tests for predicting performance in concrete. The conclusions of the study was summarised in a paper by Stewart et al. (2007).⁴⁶ Three tests were identified that correlated well with concrete performance:

- The methylene blue test - AASHTO TP57 (AASHTO, 2000)⁴⁷
- A particle packing assessment by the weight of microfine aggregates adhering to a single drop of water (Bigas and Gallias, 2002)⁴⁸
- The loose packing tests - ASTM C 1252 (ASTM, 2005)⁴⁹.

Kandhal et al. (1991)⁵⁰ realised a need to quantify the shape and texture of fine aggregate so that it could be specified on a rational basis rather than generically. In a study a total of 18 fine aggregates (8 natural sands and 10 manufactured sands) of different mineralogical compositions were sampled from various sources in Pennsylvania. Particle shape and texture data was obtained using ASTM D3398 (Standard Test Method for Index of Aggregate Particle Shape and Texture)⁵¹, and National Aggregate Association (NAA)'s two proposed methods. A particle index value of 14 based on ASTM D3398 appears to generally divide the natural sands and manufactured sands, and therefore, could be used for specification purposes. According to Kandhal, the current ASTM D3398 test procedures are however too time consuming because each sieve size fraction needs to be tested individually and results combined. Test data obtained in this study indicates that only the major fraction needs to be tested because its particle index has a fairly good correlation with the average particle index.

In a PhD. project by Järvenpää (2001)⁵² the quality characteristics of fine aggregates was assessed in order to evaluate their effects on concrete. The aim of the study was to identify which fine aggregate characteristics were important, and additionally to relate the extent of the effect that the aggregate had on the concrete as compared against the effect of the changes in mix design. Results from experiments show that the effect of the fine aggregate characteristics on the flow value was greater than the effect of the cement amount. Classification of the surface area of fine aggregates was shown to be an important parameter.

In a Round-Robin test by Ferraris (2002)⁵³ it has been shown that laser particle size distribution is the most accurate test for determining particle sizes for cement, which is of similar size to microfine aggregates. Laser size distribution was more accurate than hydrometer sizing, sizing through image analysis, sieving, and electrical zone sensing. In this method, a laser is directed through particles dispersed in a gas (aerosol) or liquid (suspension). These methods are commonly referred to as the “wet” method and “dry” method, and one can generally achieve a better dispersion using the wet method and an appropriately selected liquid medium. Interpretation of the diffraction pattern from particle shadows gives information on particle sizes. This technique can be used to grade particles as small as 0.4 to 3.5 μm up to 2 mm.

In a paper by Persson (1998)⁵⁴ a method was presented for the characterization of the fine fraction of natural and crushed aggregates, using image analysis. The aim of the characterization was to investigate the differences in particle shape and size distribution among a wide range of natural and crushed fine aggregate materials. The study involved materials from 26 different gravel pits and rock quarries from different parts of Sweden. Material <63 mm was analysed using a scanning electron microscope (back scatter mode), Fractions 63–125 mm and 125–250 mm were analysed in thin sections, using polarization microscopy with UV-light. The thin sections were prepared using epoxy mixed with fluorescence. The results show that image analysis of aggregates gives multiple possibilities of characterization and classification depending on the intended use of the material. There is a major and distinct difference between the shape of crushed and natural aggregates. Measurements of the aspect ratio (“Fshape”) of different fractions of the aggregate shows that the largest differences between materials occur in the fine fractions, i.e. material <250 mm. From that follows that the particle shape of an aggregate material is not the same for all fractions. Fine particles are much more elongated and/or flaky than large particles. Development of a general method for converting size distributions into the traditional volume or weight distribution was recommended.

4.2 Standards and Specifications

As pointed out by Goldsworthy³⁹, current specifications in some countries do not allow high percentages of fines to be used in concrete even though current research and practice proves that it is beneficial. These specifications are still based on the use of natural sands, where manufactured sands need however to be treated differently. According to Goldsworthy³⁹, the New Zealand Standards Association has incorporated a performance-based specification for concrete aggregate. There is no specified grading limit imposed by this specification. Alternatively there are limits put on the flow time and void content of the fine aggregate when tested in accordance with the New Zealand flow cone. Similarly there is no restriction on the percentage passing the 75 µm test sieve.

Meininger (2005)⁵⁵ reports that one controversial topic now working its way through the ASTM process is whether to allow more crushed aggregate fines in concrete aggregates. The principle concerns are the higher drying shrinkage that may be involved and the potential problems with batching higher-fines aggregates through typical concrete plants. This rationale is based upon an extensive study by the International Centre for Aggregates Research and the University of Texas at Austin (Ahn & Fowler, 2001)⁵⁶ where some of the effects of high-fines on the properties of cement mortar and concrete were studied. A total of 50 sands were used in this mortar study, 10 of which were included in the concrete research. A summary of aggregate characteristics that affect the properties of mortar and concrete are presented along with the correlations evaluated between these properties.

In the European Standard EN 12620 (2002)⁴; Aggregates for concrete, definitions are given for; fine aggregate; as the smaller aggregate sizes with D less than or equal to 4 mm. It is noted that fine aggregate can be produced from natural disintegration of rock or gravel and/or by the crushing of rock or gravel or processing of manufactured aggregate. Definitions of filler aggregate is aggregate, where most of which passes a 0,063 mm sieve, which can be added to construction materials to provide certain properties, and fines is defined as particle size fraction of an aggregate which passes the 0,063 mm sieve.

In a proposed review version of the standard, the standard fines of the fine aggregate or all-in aggregate shall be considered non-harmful when any of the four following conditions apply:

- a) The fines content of the fine aggregate or all-in aggregate is not greater than 3 % or other value according to the provisions valid in the place of use of the aggregate;
- b) The sand equivalent value (SE) when tested in accordance with EN 933-8 exceeds one of the following limits:

Sand equivalent	Category
≥ 60	SE ₆₀
≥ 50	SE ₅₀
≥ 40	SE ₄₀
≥ 35	SE ₃₅
≥ 30	SE ₃₀
< 30	SE _{Declared}
No requirement	SE _{NR}

- c) The methylene blue value (MB) on 0/2 mm fraction when tested in accordance with EN 933-9 gives a value less than the following limits:

Fine aggregates		All in 0/D	
MB value g/kg	Category	MB _{0/D} = MB x passing the mm sieve ⁽¹⁾ g/kg	Category
≤ 2	MB ₂	• 0,8	MB _{0/D0,8}
≤ 2,5	MB _{2,5}	• 1	MB _{0/D1}
≤ 3	MB ₃	> 1	MB _{0/D} Declared
> 3	MB _{Declared}		
No requirement	MB _{NR}	No requirement	MB _{0/D} NR
⁽¹⁾ MB _{0/D} is MB measured on 0/2 mm fraction and reported on 0/D mm			

- d) The methylene blue value (MB_F) on 0/0,125 mm fraction when tested in accordance with EN 933-9 gives a value less than the following limits :

MBF value g/kg	Category
≤ 10	MB _F 10
≤ 25	MB _F 25
> 25	MB _F Declared
No requirement	MB _F NR

- e) Equivalence of performance with known satisfactory aggregate is established or there is evidence of satisfactory use with no experience of problems. It is noted that the compliance requirements for sand equivalent test and methylene blue test should normally be expressed with a probability of 90 %.

An amendment was made in 1998 to Australian Standard AS 2758.1 (Standards Australia, 1998)⁵⁷, increasing the acceptable level of <75µm size to 20% of the crushed fine aggregate, in contrast to natural sand where the limit is 5%.

However, although all major quarrying companies have made significant progress in using manufactured sand, there is little common agreement on which tests might be applied to the product or what limits should be specified for supply of the product. As a consequence Cement Concrete & Aggregates Australia (CCAA) established a sub committee in November 2004 to develop a research project that would recommend national test methods and specification limits for manufactured sand. A research report was published in 2007⁴¹.

The following objectives for the research project were established:

1. To determine the most appropriate aggregate tests for quality control and specification of manufactured sands
2. To determine the 'repeatability' of the aggregate tests.
3. To determine specification limits for the aggregate tests which would ensure the supply of fit-for-purpose manufactured sand
4. To present a body of research findings to Standards Australia which would be sufficient to support an industry submission for the specification of manufactured sands for use as fine aggregate in concrete.

5 Developments in Production and Use of Manufactured Aggregates

The development of a technology (production and use) for manufactured aggregates has been driven by need. Thus we see that R&D on this topic internationally varies very much in dependence of the resources available. Japan is an example of a country that early started developing and applying new technologies, since their natural sand resources got totally depleted many years ago. On the opposite side, North American – especially Canadian – resource conditions have been (and still are) of an order that do not call for alternatives to glaciofluvial sand/gravel as aggregate.

More than many European countries, Norway has been abundantly supplied with natural aggregates for construction purpose. Traditionally most concrete aggregates have been produced on the basis of glaciofluvial sand/gravel deposits, which offer rich but unevenly distributed resources throughout a country characterized by large transport distances.

During the last decades, however, crushed materials from hard rock quarries have won an increasing market share towards ready mixed concrete, besides also being the main product for asphalt pavements and road construction. As evident in Table 5-1, sand/gravel constituted about 37% of the total aggregate production in 1999, while the corresponding figure in 2007 was only 22% (Bergvesenet & NGU 2008)⁵⁸. Reasons for this may be found in technical, as well as in economic and environmental circumstances:

1. With an uneven geographic distribution of sand/gravel resources when it comes to quantity as well as performance properties - e.g. Alkali Aggregate Reaction susceptibility, physical strength, grading, contamination and mica content; the key principle of keeping ready mixed concrete a local business has called for alternative solutions to the transport of natural aggregates from far away sources.
2. Selecting aggregates according to the specific properties of the quarry rock type, offers to the ready mixed concrete producer the option of designing his concrete with regards to performance characteristics like elastic modulus, maximum obtainable strength, abrasion resistance, density, durability, fire resistance, workability and aesthetic appearance.
3. Many of the most valuable sand/gravel resources are being rapidly depleted, for which reason a shortage situation is not too far away. Like in most industrialized countries, the annual Norwegian consumption of aggregates is of the order of 10 tons per capita. The theoretical volume of sand/gravel should allow for a satisfactory aggregate supply for a few hundred years. However, the fact that about half the total resources are located far from the densely populated areas – and 50-80% of the nearby resources are not available for different reasons – point at a supply shortage of sand/gravel within less than 30 years. That is – unless the pattern of use is changed (Danielsen 1999)⁵⁹.
4. From an environmental point of view this will also cause a conflict of interest versus alternative ways of considering the resources; e.g. for ground water supply, as building ground or agricultural land, or simply for the preservation of landscapes and geological key locations.
5. Once operating a hard rock quarry for e.g. road material purposes, the aggregate supplier may find it beneficial from an economic point of view to extend his range of products and market areas in order to obtain a more total utilization of the different aggregate sizes resulting from the production.

Table 5-1. Development in production; sand/gravel vs. crushed aggregates (production in thousand tons) (Bergvesenet & NGU, 2008)⁵⁸

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007
Crushed aggregates	39.000	34.000	38.000	35.000	36.000	37.000	38.000	45.947	51.533
Sand/gravel	23.000	19.000	15.000	15.000	15.000	15.000	15.000	13.418	14.855
Total	62.000	53.000	53.000	50.000	51.000	52.000	53.000	59.365	66.388
%-sand/ gravel	37	36	28	30	29	29	28	23	22

5.1 Previous Norwegian Experience and Practical Development

In Norway manufactured stone sand was used on a large scale for the construction of Førrevassdammen as early as in the years 1982 – 1986. Førrevassdammen is double curved arch dam, 15 meter thick, with gravity dams at both sides. Maximum height is 96 m and the length is 1.300 meter. The concrete volume is 250.000 m³. The dam is situated at the high mountain at 1.000 meter above sea level in Rogaland country. It belongs to the Statkraft Ulla-Førre-plant which is the biggest hydro power plant in Europe. By reason of the tough weather conditions at the construction site, the construction of the dam could only be executed at the summer months.

No natural sand/gravel aggregate resources were available close enough, so all aggregates for the concrete production had to be produced on site. Hard rock for the production of manufactured sand was taken from a quarry close to the site. The rock was a gneiss-granite. In addition to the concrete for the dam, also some 50.000 m³ of normal construction concrete for different use at the hydro power plant was produced.

The production plant for the manufactured sand was based on three crushing steps. The final step was a horizontal impact crusher with horizontal shaft (Hazemag APK 1313). The separation was done in a wet process. The aggregate was split in the following fractions: 0.04/1 mm, 1/4 mm, 4/10 mm, 10/30 mm, 30/60 mm and 60/120 mm. The separation down to 4 mm was done by normal wet screening. The separation at 1 mm was done in a Rheax column and the separation at 0.04 mm was done by cyclones and lamella classifiers. The speed of the impact crusher was regulated between 30 and 55 meter per second in periphery speed to get balance in the volume of the fines grading. High speed made high production of the finest grading, but also high consumption of wearing steel in the crushers. In general there was an overproduction of the grading 1/4 mm. This was a consequence of the mineral composition, the dominating crystal size etc. in the rock.

The concrete for the dam was of two types. The concrete closer than 1.5 meter from the surface was a frost resistant surface concrete with d_{max} 60 mm. The rest was an inner concrete with d_{max} 120 mm. In the surface concrete there was 210 kg cement per m³ and in the inner concrete 150 kg. In addition to that, 16 kg of silica fume was used for both recipes. The cement contained 30% fly ash. The demand for characteristic strength for the surface concrete was 30 MPa and for the inner concrete 25 MPa. The normal construction concrete that was made was a C30 quality with d_{max} 22 mm and 325 kg cement per m³.

The experience with the production and use of this concrete can be summed up like this; to the object the concrete was used to, nothing important was different from what it had been with corresponding concrete produced from natural sand and gravel. Poor shape and texture was to a certain extent compensated by a very good control with the grading of the aggregate. The grading for the dam concrete was very similar to a Füller curve. For the grading for the normal construction concrete a gap-graded curve was used. A great deal of the construction concrete with d_{max} 22 mm was pumped.

One negative experience observed was a tendency for bleeding of the fresh concrete. The fine aggregate had a lack of fines (filler) smaller than 0.06 mm. The aggregate separation plant could not be adjusted to increase the fines content enough without reconstruction and it was decided to live with this small problem in the construction period.



Figure 5-1. The construction of Førrevassdammen. (photo; Statkraft, www.energifakta.no)

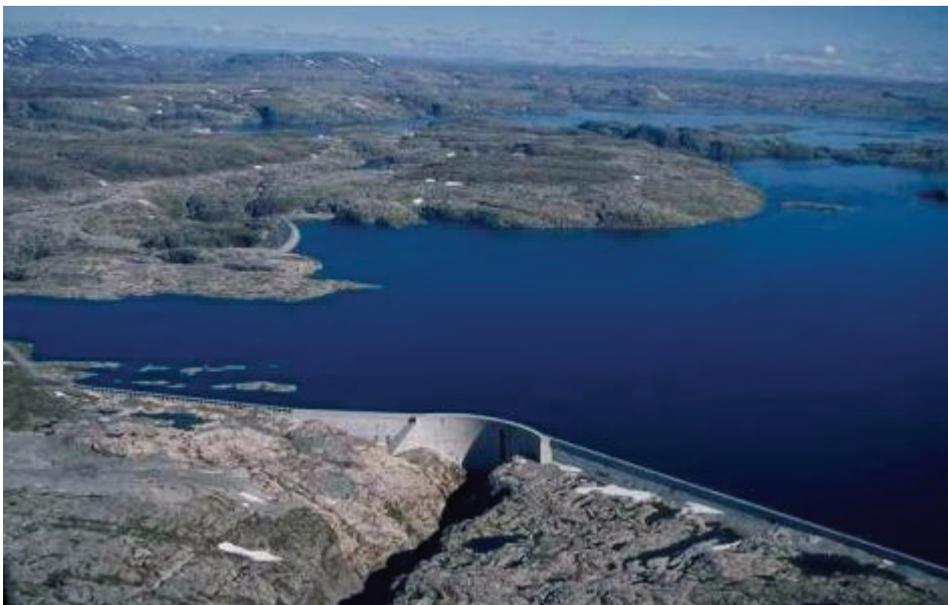


Figure 5-2. Førrevassdammen completed. (photo; Statkraft, www.energifakta.no)

A systematic development in applying manufactured sand started in the early nineties, led by the quarry and concrete company Franzefoss Bruk AS, and assisted by the research organization Sintef. Several R&D projects have been carried out during the last 10-15 years, partly with public sponsoring, and with participants from the quarry industry as well as ready mixed concrete, concrete admixtures, suppliers of quarry machinery and end-users (Johansen, Laanke & Smeplass, 1995)⁶⁰ (Ørbog, 1998)⁶¹, (Karlsson, 2000)^{62,63}. These activities have also been strongly linked to teaching and student training at the Norwegian University of Science and Technology –NTNU (Ørbog 1996)⁶⁴, (Bjøntegaard & Fredvik, 1997)⁶⁵, (Wallevik, 2000)⁶⁶, (Aslaksen Aasly, 2002)⁶⁷. In addition, several aggregate producers have put significant investments into new processing equipment and systems to improve aggregate properties. Efforts have also been put into practical application technology in concrete plants, in order to utilize high amounts of manufactured aggregates. Figure 5-3 shows the development in use of manufactured sand in concrete (Franzefoss plants) in the period 1990 to 1999.

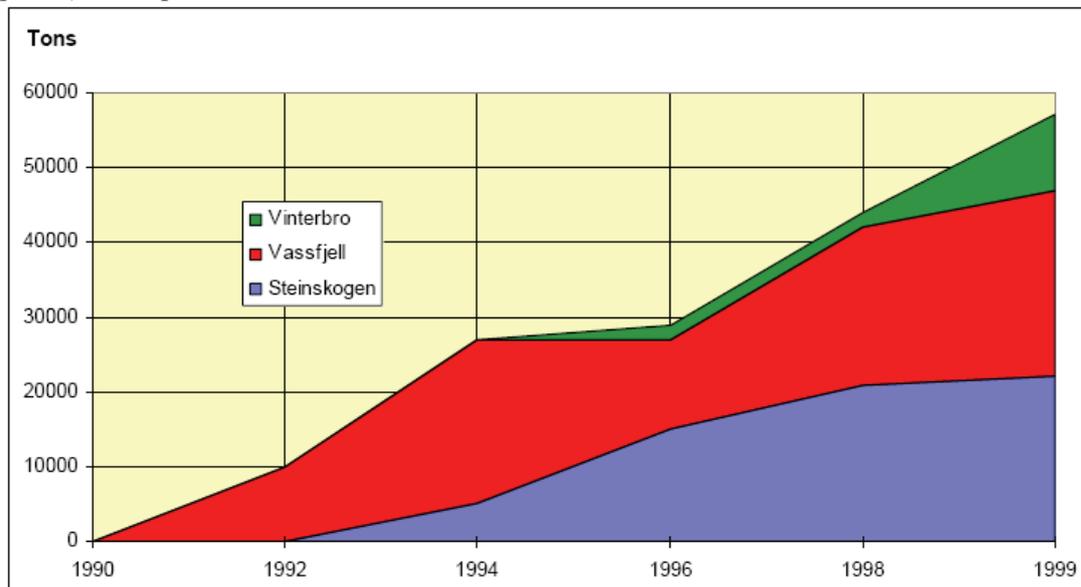


Figure 5-3 Use of crushed gravel in concrete delivered from three of Franzefoss plants.⁸

5.2 Directions of R&D

R&D activities have to a large degree been directed to solve two principal problems:

1. To develop an aggregate production that can deliver more cubical materials in all critical sizes, and still keep a control with the total mass balance and avoid excess volumes of fines.
2. To develop a concrete mix design system that can deliver economically and technically feasible recipes with the more sharp angular and fines containing crushed aggregates.

Development in concrete mix design

It may be correct to claim that the materials technology and mix design philosophy in different countries is very much based on the aggregate resources locally available. Thus we will find different rules, specifications and practice in e.g. countries with predominantly well-sorted and rounded river sand aggregates – low in fines as well as in coarse gravel – compared to countries with predominantly glaciofluvial sand/gravel – which may be more sharp angular as well as less well sorted.

These differences may be one of the major obstacles in the harmonizing of common, international materials standards and specifications, and a challenge when it comes to transferring experience (and materials) from one country to another.

The incorporating of manufactured sand into concrete recipes is even more challenging, due to the very high fines content, dense grading curve and sharp angular particle shape of these materials. The Norwegian approach to mix design has been to play with the aggregates – i.e. try to tailor recipes for the aggregate properties, instead of using a lot of money to change these e.g. by fines removal. A sharp angular (and even more a flaky) aggregate will have higher void content/looser packing than a well rounded one, given the same grading. This calls for a denser grading curve and higher fines content in order to obtain the same internal stability – which is also what we find in manufactured sand.

The effects that varying water cement ratios and superplasticiser have on concrete containing manufactured sand as a complete replacement for natural sand is studied in a project by Krinke (2004)⁶⁸. It is claimed that due to current levels of construction in Australia there is an ever decreasing availability of natural sands suitable for use as a fine aggregate in concrete. Krinke reports that there are a number of drawbacks to the use of manufactured sand, particularly the poor workability and finish obtained. This is caused by the high fines content (<75 microns) and the irregular particle shape of the manufactured sand. For these reasons manufactured sand has a very poor reputation in the construction industry. In the study by Krinke an experimental approach was taken to study the effect of the varying water cement ratios and the effect of the superplasticiser. The properties of various concrete mixes were assessed by measuring both the fresh and hardened state properties of the concrete mix. The results of the tests showed that a reasonable workability and a medium strength could be achieved with a high water cement ratio in a concrete mix. The addition of a superplasticiser to a concrete mix allows the mix to achieve a high strength while also having a good workability.

It has been pointed out by Dilek et al. (2006)⁶⁹ that designers, specifiers, contractors and material suppliers need to understand the effects of manufactured sand angularity as well as fines content on concrete water demand and concrete durability. As part of a comprehensive research program, manufactured sand properties and their effects on fresh and hardened concrete properties were investigated. The effects of manufactured sand properties on water demand of mortar and concrete were investigated. Manufactured sands with a wide range of particle angularities and fines contents were included in the testing program. Results of mortar testing confirmed that angularity influenced the water demand of mortars. The fine particle content of manufactured sands was also found to contribute to water demand of mortars. The results of sand and mortar testing were used to develop a subsequent testing program examining the effects of manufactured sand properties on concrete water demand. A statistically based water demand model was developed for conventional strength concrete. The contribution to water demand was found to be primarily related to the angularity of particles with secondary contribution from quantity of fines. Effects due to gradations were not found to be significant.

The relationships between manufactured sand characteristics and hardened concrete properties were discussed in subsequent papers by Dilek & Leming (2006)⁷⁰. Concrete containing commercially available manufactured sands with a wide range of particle angularities and fines contents were included in the laboratory testing program on de-icer salt scaling. Angularity of particles and quantity of fines were found to contribute to salt scaling.

Manufactured sand to improve the total sand grading

Using limited amounts of manufactured sand to improve the total sand grading, where the initial natural sand is e.g. low in fines, and/or has a particularly “open” grading. This approach could be successful in cases where low fines sand was to be used for low cement content concrete (low/ordinary strength), and especially to counteract segregation and bleeding in high-slump mixes. The limitation was connected with the fact that there was no change in mix design philosophy; the crushed aggregate was to be used more or less like any other aggregate – taking advantage of a finer grading only – and also having to accept the disadvantages of particle shape and in many cases extremely high fines content. Thus it was concluded that in most cases the incorporating of manufactured sand resulted in a less workable, more water requiring mix.

Table 5-2 compiles some of the general benefits/disadvantages normally connected with the use of manufactured sand in concrete:

Table 5-2: Manufactured sand in concrete – general properties

Concrete functionality	Benefits	Disadvantages
General properties	Less prone to bleeding and segregation Better pumpability	Higher cohesion may also entail more need for vibration and cause a higher water requirement
Concrete for walls	Surfaces without visible voids/smooth surfaces	
Concrete floors	High fines content provides good results by steel finishing Good workability for low consistency concrete,	Incorrect vibration may cause a concentration of fines in the top layer.
Low consistency concrete in general	Workability in spite of low slump values, and cement content	
Shotcrete	Less waste from sprayed surfaces. Reduced need for accelerator	Higher wear on equipment due to abrasion
Foamed concrete	Gets a higher fines content Smaller D_{max} can be used Less prone to segregation	

Particle/matrix approach

In the PhD. work of Mørtzell (1996)⁷¹ it was applied a proportioning philosophy in line with the so-called particle/matrix approach (like for SCC) to obtain a matrix rich concrete in order to counteract internal friction from sharp angular aggregates. In such a mix, we will still consider the frictional properties of the coarse size fractions (also in the “sand”), while the finer particles, however, are kept flocculent in the viscous fluid – for which reason the particle shape becomes less important. Chemical admixtures will be used to reduce viscosity, while the aggregate fines will contribute to counteract segregation and bleeding. Especially polymer-based plasticizers have proved efficient for this purpose (probably depending on the mineral composition of aggregates). A consequence of this approach is that considerably higher amounts of manufactured sand are used – research has shown that an optimum content may be found for a specific mix, depending on the total aggregate and mix of constituents. Besides, the total fines (and matrix) content needs to be controlled, which can result in reducing the part of cement and silica content that is not directly necessary for strength purpose. It further follows from this consideration that substantial percentages of manufactured sand will first of all be feasible for concretes in the low-medium strength level, where the necessary amount of binders is limited. For such mixes it has been found that workability may be kept unaltered, or even improve up to a crushed sand percentage of 40-50, above which the mix will become increasingly viscous (“sticky”) and will require high volumes of plasticizer.

Advantage of the latest crusher developments

Taking advantage of the latest crusher development – to compensate sand curves with the addition of a cubical medium sized aggregate (e.g. 4-8 mm): One major development from the new Rhodax concept was the cubical particle shape even in the critical, intermediate sizes. This could open for a use of e.g. the 4-8 mm crushed fraction to improve the total grading for the benefit of workability and stability, as Norwegian natural sands are often low in this size range.

An example of this development (some key figures for a standard C35 concrete, Trondheim) is in Table 5-3, where some rather unsuitable parent rock was used to produce manufactured sand.

Table 5-3: An example of mix design change (SINTEF 2002-2004)⁷²

Components – kg/m ³	Original recipe and aggregates	New recipe and aggregates
Cement – Silica fume	355 – 10	306 – 0
Manufactured sand 0-4 mm – Natural sand 0-8 mm	368 – 656	412 – 617
Crushed 4-8 mm, 8-16, 16-25	0 – 350 – 550	165 – 248 – 618
Viscocrete 140 - Plastiment BV-40	0 – 2,95	2,45 - 0
Water – w/c ratio	219 – 0,60	184 – 0,60
Total matrix – total fines (<0,125) l/m ³	388 – 169	321 – 137
Slump – flow value (mm)	200 – 520	215 – 580
Compressive strength (MPa) 1 – 7 – 28 days	10 – 26 – 44	14 – 29 – 43
Shrinkage % ₀ 7 – 21 – 49 days	0,3 - 0,54 - 0,65	0,19 - 0,33 - 0,50

Unfortunately, however, the practical use of this crusher concept proved to be difficult, as discussed earlier in this report. So although the theoretical options were promising, a further implementation of this concept will have to await a possible further development of the equipment.

Instead, a development of “traditional” crushing set-up (cone, VSI) in combination with classification based on modern wind sieving, has resulted in a sand aggregate with materials properties on the level of a good natural sand – with even less grading variations than normally found in a glaciofluvial sand deposit. Further, this process has enabled the production of a well controlled filler fraction, with a particle size distribution quite similar to that of cement. In Norway this kind of manufactured aggregate has been successfully applied both for ready-mix concrete and for paving blocks – the latter with high requirements to compaction. Actually, with this manufactured aggregate the mix design will be less different from that normally used with Norwegian natural aggregates.

Tailored chemical admixtures

The importance of adapting mix design principles to local, geological conditions must be emphasized. This applies to mineral composition as well as to the geometrical properties.

Research has been undertaken developing tailored chemical admixtures – taking the mineral composition as well as the specific geometric properties of the mix into consideration. This is a development, which still has an un-realized potential. E.g. have aggregates with different mineralogical composition (especially in the smaller size fractions) revealed different reactions to different kinds of super plasticizers. And it is also important to tailor the admixtures with respect to fines content and grading to optimise the rheological properties (reduced viscosity versus bleeding and segregation).

5.3 Some International Key Projects

In the MinBaS I program (2003-2005) - “Utilization of alternative aggregate types in concrete”, Lagerblad (2005)⁷³ reports on; “Crushed rock as concrete aggregate” in a compilation report, as one of 6 sub-project reports from the project. The project has basically focused on the fine aggregate < 2 mm. This is the most difficult part of the aggregate curve with respect to shape and flakiness, because in these lower fractions the content of free mineral particles is generally high. A main goal for the project was to look into the correlation between petrographic properties (mineralogy and texture) and fresh concrete properties. In the project it is concluded that it is generally possible to use crushed aggregate from granitic rocks as concrete aggregate, also as fine aggregate. It was found that there are relatively large differences among aggregates from different rocks with respect to grading curve (in particular the amount of filler), shape and flakiness, amount of free mica and variation. This means that the effect on fresh concrete properties varies a lot depending on the chosen rock. Materials from all the tested rocks were found to be suitable as fine concrete aggregate. However, the variation is very large. Some of the rocks give aggregate of good quality, rather close to the quality of the natural reference gravel. On the other hand, other aggregates require very high cement and water contents (or increased amounts of plasticizer) to give workable concrete. This is a very significant disadvantage due to technical and economic reasons. It was found that washing of the fine aggregate and by this removal of the finest part of the curve (< 10 microns) will in most cases improve the workability of the concrete. One conclusion from this study is that the shape of the 0/2 mm fraction is generally dependent on the mineralogy (and texture) and is not much dependent of the crushing process. Generally it is reasonable to believe that finer crystal sizes are beneficial and makes it easier to produce particles with cubical shape. Another important conclusion from this Swedish study is that the mix design approach has to be changed due to the fact that crushed aggregate is less cubical with a rougher surface texture. It is thus a challenge to develop mix design specially designed for crushed aggregate. It is likely that the “ideal” grading curve

will look different for crushed than for natural aggregate. In particular, it is important to have a closer look on the ideal filler amount (and even the ideal filler grading). It is also likely that the change from natural to crushed aggregate will require other types of plasticizers, and even new types of cements.

As a follow-up to the MinBas I program, two new projects have been started with Swedish governmental support in 2007. The Swedish Energy agency (STEM) is supporting a project aiming at developing tools to facilitate the introduction of crushed sands in concrete including a mix design program, guidelines for establishing rock quarries, guidelines for specification of aggregates suitable for concrete production. The second project (MinBas II) is dealing with guidelines for air classifiers and crushers and durability questions. The projects will continue until the end of 2010.

A Nordic project with participants from Norway, Faeroe Islands, Iceland and Greenland was finished in 2004 (Wigum et al., 2004)². The project was funded by NORA (Nordic Atlantic Co-operation) in addition to work contribution from the participating parties. In the project a review of the present state-of-the-art knowledge regarding production and use of manufactured sand in Norway was provided. In addition the current situation in Iceland and Greenland was evaluated in order to enable utilisation of these novel techniques. Icelandic aggregate production has mainly involved quarrying natural sand and gravel deposits. It is however expected that production of manufactured sand will increase in the future. The report gives an overview of the situation in Iceland, including structure of the aggregate industry, production volumes, research and experiences, and some future consideration of the utilisation of manufactured sand in Iceland. The situation in Greenland is reviewed including production of crushed rock, sea dredged materials and glaciofluvial sand and gravel. An overview is given of the Greenland Recommendations for concrete structures, along with experiences from a construction site where import of sand was necessary. Finally the market conditions and future potentials in Greenland are considered.

Governmental restrictions and uncertain future resources of natural sand have made the search for alternative materials an urgent matter in order to secure the future supply of concrete aggregates in the Göteborg region in Sweden (Skoog, 2008)⁷⁴. A project was thus initiated to find a long term aggregate solution. Even though a few different alternatives have been assessed within the project the main focus has been to utilise manufactured sand from the Jehander pit in Källered, just south of Göteborg. Preliminary results from laboratory concrete tests showed that the replacement of natural sand 0/8 mm with corresponding manufactured fraction resulted in a substantial increase of the water demand as well as reduced workability for the concrete. The differences were believed to be due to an increased amount of fines <0.063 mm in combination with poorer particle shapes of the crushed material. Some alternative measures to improve the crushed sand were thus assessed and a production process that included the use of a VSI-crusher in combination with air classification was eventually selected. Full scale tests verified that VSI-crushing improved the particle shape. Another important effect of the selected crushing method was to even out the particle size distribution. It was further verified that the content of fines could be significantly reduced by air classification.

Rogers (2008)³⁵ reports that manufactured sands have been used in Canada for over 50 years. Since the 1950's manufactured sands have been rarely used in hydraulic cement concrete. The reason is the generally unsuitable behaviour of such sands in concrete, the high cost of manufacture and the general availability of natural sands. Even in markets where natural sands are not locally available, natural sands will be brought into the market rather than adopt the use of locally made manufactured sands. Concrete sand probably only makes up about 10 % of the combined market for concrete and hot mix asphalt fine aggregate. It is foreseen that the use of manufactured sands will gradually increase in Canada and North

America. This will be driven by both the depletion of local sources of natural sand and the high cost of natural sand in certain markets and also because of the beneficial engineering properties of manufactured sands. The test methods that we have used to evaluate natural sands will need modification and new criteria and test methods will have to be adopted to properly evaluate the properties of these new materials.

In Sri Lanka, the National Building and Research Organization (NBRO), together with the Urban Development Authority (UDA), has since 2001 promoted manufactured sand as a solution to the country's sand shortage problem. Dredged sea sand, manufactured sand and dune sand have been presented as alternatives to river sand mining of which has now been banned by the Government. However, as the use of both dune sand and dredged sea sand pose environmental problems, both organizations are promoting the use of manufactured sand for this purpose. NBRO says that manufactured sand will not pose an environment risk as Sri Lanka has an abundance of high quality stone quarries. Several sites have already been identified for this purpose. According to the NBRO, investors are planning to import equipment and plants will be set up in two or three key locations after clearance from environmental authorities.

In an article by Kuhar (2005)⁷⁵ the case of the company Chantilly Crushed Stone which is serving the Washington, D.C., area, is described with emphasises of manufactured sand. The company supplies stone most importantly to a ready mix plant and asphalt plant leased to other companies on the quarry property. It is claimed that one of the reasons that manufactured sand production is so successful is that it starts with a clean, friable rock. The centerpiece of the company's manufactured sand process is a bivi-TEC dry, dual- vibratory screen manufactured by Aggregates Equipment Inc., Leola, Pa. When the part of the plant was set up it was looked for a way to make sand using a dry process. According to Aggregates Equipment Inc., the operating principle behind the bivi-TEC is simple. To assure the most effective screening, high-acceleration forces must be transferred to the feed material. The bivi-TEC achieves these high forces by dynamically tensioning and relaxing the flexible screen mats using a dual-vibration principle. Enhanced by resonance, one drive can produce two vibration movements. The screen box is accelerated approximately 2 g's while the screen mats can receive up to 50 g's. For Chantilly Crushed Stone, the other advantage to using a dry process system was the ability to make sand year 'round. Chantilly Crushed Stone wanted to manufacture sand as a strategic move to increase its product line. The company was able to accomplish that successfully and add to an already successful operation.

In an article by Constantino (2005)⁷⁶ the company's Pompton Lakes, N.J. is presented which recently chose to supplement its product line with manufactured sand. Making such a change was not in itself significant. What was significant is that it chose to bypass traditional wet classification methods, opting instead to go with a dry classifier to create its product. The result has been a high-quality product that is virtually impossible to keep in stock and a dramatic savings in manufacturing and processing costs. The production manager is expressing the following experiences:

"We've been at this same site since 1956 and primarily produce 3/4-in., 3/8-in., 1/4-in. products, as well as screenings," Gallo says. "The overwhelming bulk of the material is used in asphalt and concrete ready-mix operations. A couple years back, as the demand for those materials continued to grow, we realized that there could be real value and savings in creating our own manufactured sand product. "We had definite criteria for what we wanted in a classification system, including durability, economy, seamless integration into the overall plant and a preference for not using a water-based system. We did some research," Gallo says, "contacted representatives from Buell, and they were willing to bring a portable classifier plant out, and demo their system here at our site. Once we saw what it could do, we made the commitment."

"Prior to installation of the Buell unit, we weren't doing any classification, so the immediate impact is that we now have a new, highly sought-after product. In fact, every pound of the material we produce is consistently sold and/or utilized. In addition, we are using it directly in our asphalt operation, but since it is now a dry material, we have eliminated the drying step, resulting in a very nice reduction in our fuel costs."

Many countries have been using manufactured sand in concrete for many years, and according to Goldsworthy³⁹, the New Zealand concrete industry has used high fines manufactured sand in concrete mixes for at least 30 years. He reports that experience and practice has demonstrated that not only can manufactured sand be used successfully as a substitute for natural, but also in many cases it will have superior performance. Understanding not only the effect of grading, but also shape and surface texture on fine aggregate performance in concrete is the key to successful use. Some past experience of manufactured sand has been negative due to incorrect processing and proportioning of sand in the concrete mix. Manufactured sand has been used as a direct 1:1 substitute for traditional sands leading to misleading results and feelings about its use. However, if the material is treated correctly it is claimed by Goldsworthy that it will perform well in both fresh and hardened concrete.

Hashimoto (2008)⁷⁷ has reported about some actual cases in Japan, where the V7 sand making system has been used in order to produce concrete fine aggregates. In one case a ready-mixed concrete plant went from using 100% of sea sand to 50% of V7 sand. This resulted in a reduction of unit water content by 7 – 9 kg. In another case, a ready-mixed concrete plant went from using 100% of sea sand to 100% of V7 sand. This resulted in an improvement of the workability of concrete. Finally it is reported a case of a ready-mixed plant achieving saving of 11kgs of unit water content and 15-20kgs of unit cement content.

In Australia, O'Flynn (2000)¹⁵ reported that the closure of the Brisbane River to extractive dredging and the exhaustion or limitation of other sand sources have caused an industry shift to manufactured sand for concrete fine aggregates. It is reported that it is produced in 12 of the major hardrock quarries in southeast Queensland. Companies have achieved only partial replacement of natural sands, to around 40% of the fine aggregate component in their concrete mixes. While improved technology and management will further reduce the amount of natural blend sand required, it is unlikely to be fully replaced in the foreseeable future. Manufactured sand in the area are gap-graded, with a high proportion of coarse grit and some <75µm filler, but only a small percentage in the fine to medium sand (0.06-0.6 mm) sizes. For a satisfactory particle size distribution this must be supplemented with alluvial or marine sands. Although providing a solution to one problem, manufactured sand raises new environmental issues. The management of fine wastes is likely to become an important issue, as will the increased demand for natural fine sands to improve mix grading and workability. Diminishing supply from land-based sources has resulted in increased applications for dredging of Moreton Bay, where enormous resources occur and low impact extraction may be possible. However, this prospect raises difficult environmental and land-access issues for government decision makers.

Stewart et al. (2007)⁴⁶ showed by performance tests of concrete that micro fine aggregates can be incorporated into concrete at levels of 15% by volume of the sand without detrimentally affecting hardened concrete properties of strength (compressive and flexural), chloride ion penetrability, and abrasion resistance. However, the use of microfines does increase water or water-reducer demand somewhat.

The Building and Construction Authority (BCA) in Singapore encouraged in the end of 2007 the use of crushed rock sand as replacement of natural sand since this is a viable alternative to natural sand and will help ease our reliance on natural sand for concrete. In a letter from

BCA it is stated that: “..... recent surveys show that crushed rock sand, in the form of granite dust, is often used as fine aggregate to replace natural sand in various proportions. Singapore Standard SS 31: Specification for Aggregates from Natural Sources for Concrete permits the use of crushed rock sand to totally replace natural sand for concrete. Studies and trial tests conducted in Singapore have demonstrated the suitability of crushed rock sand for use in concrete as total replacement of natural sand. In fact, there are already a couple of ongoing projects that are using 100% crushed rock sand as fine aggregate in concrete. However it must be noted that the quality and grading requirements of the crushed rock sand shall be in accordance with SS 31. With some adjustment to the concrete mix, together with the appropriate use of admixtures, it has been shown to be feasible to produce concrete that meets the required strength and workability requirements”.

6 Information about Parties dealing with Manufactured Sand

In this chapter some information is provided regarding “who is who” in this business (outside Norway), in order to know who are working on these topics, and where it is relevant to search for information and cooperation.

6.1 Researchers/Experts

The International Center for Aggregates Research (ICAR), launched in August of 1992 as a joint operation of The University of Texas at Austin and Texas A&M University has been active providing various reports of the properties of fines and its application in concrete. Most of their reports are available at their website⁴. As listed on their website, ICAR is seeking to become the aggregate industry's "right arm" for research. Today ICAR remains committed to the vision that led to that expansion and to its goal of finding the most efficient and effective use of the aggregate industry's resources through research, education, and information exchange.

Researchers at The Swedish Concrete Institute (CBI) and The Technical Research Institute of Sweden (SP) have been engaged in research and development regarding manufactured sand. This work has been carried out in cooperation programmes, such as the MinBaS I program (2003-2005), the MinBaS II program (-2010), and the STEM program by the Swedish Energy agency.

6.2 Equipment Producers

In Nordic countries two main producers have dominated the market regarding the production of various aggregate processing equipment. These two companies are the Finnish company Metso Minerals⁵, and the Swedish company Sandvik Mining and Construction⁶. The two companies are producing a whole range of crushers for aggregate production, and both are producing Vertical Shaft Impact (VSI) crushers. Metso is producing the original Barmac VSI crusher, while Sandvik is producing CV-series VSI crushers.

Metso Minerals and Buell⁷, a division of Fisher-Klosterman, Inc, USA, have signed an agreement for the sale of Buell air classification equipment in Europe, Middle-East and Africa (on an exclusive base) and Asia.

In Japan, Kemco Kotobuki Engineering & Manufacturing co., Ltd⁸. has developed the V7; Dry sand making system, with the patented US7 VSI crusher and the patented aircscreen.

In addition to the two major Nordic equipment producers, many producers around the world produce and sell sand making equipments. Many new producers are located in China, e.g. the Shanghai Zenith Crusher and Pulverizer Company⁹, and Henan Liming Road & Bridge Heavy Industry Co., Ltd.¹⁰

⁴ www.icar.utexas.edu

⁵ www.metsominerals.com

⁶ www.miningandconstruction.sandvik.com

⁷ www.buellclassifiers.com

⁸ www.kemco.co.jp/eng/hasai/v7_top.htm

⁹ www.zenithcrusher.com

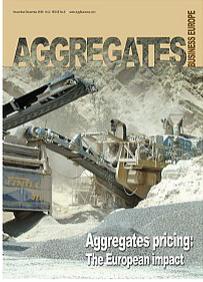
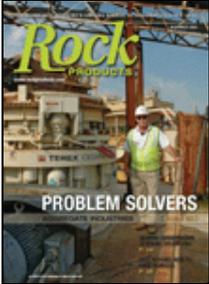
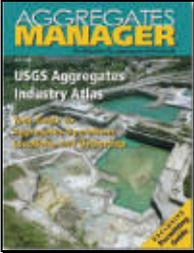
¹⁰ www.break-day.com/ver3.0/

6.3 Trade Journals & Websites

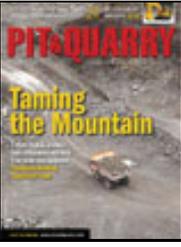
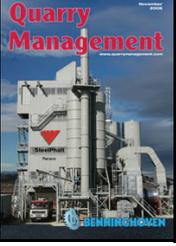
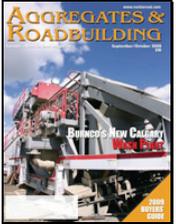
The Internet opens up for easily accessible search for information. In addition to the general Internet search engines, such as Google etc., scientific articles are to be found at the databases of e.g. ScienceDirect¹¹, which contains over 25% of the world's science and technology full text and bibliographic information. Another interactive database is SpringerLink, which is one of the leading databases for high-quality journals, book series, books, reference works and the Online Archives Collection.

Various Trade Journals are providing up-to-date information about the industry and the recent development and experience in the aggregate industry. An overview of a collection of journals is provided in Table 6-1.

Table 6-1: Overview of some Trade Journals dealing with the topic of aggregate production.

 <p>www.aggbusiness.com</p>	<p>Aggregates Business Europe was launched in 2007 to meet the information needs of the increasingly complex, competitive, and regulated European quarrying sector and provide it with an independent voice and source of information.</p> <p>The bi-monthly magazine reports on quarrying best practice in both Europe and the rest of the world, new legislation and business news.</p> <p>The website provides a daily up-date on developments in the industry, while the printed magazine brings together and provides analysis of the key developments.</p>
 <p>www.rockproducts.com</p>	<p>Rock Products has been the aggregate industry's source of information since 1896. Its staff and allied publications offer a working knowledge of the industry that promotes operation efficiencies, management solutions and innovative technologies to strengthen the bottom line.</p>
 <p>www.aggman.com</p>	<p>Aggregates Manager magazine has been published since 1996 and covers the full range of information needs for aggregates professionals. The journal serves producers of crushed stone, sand and gravel, recycled materials, cement, lime, concrete producers, asphalt producers, gypsum, potash, sand and other non-metallic minerals, hauling companies, engineering consultants, government, and others allied to the field.</p>

¹¹ www.sciencedirect.com

 <p>www.pitandquarry.com</p>	<p>Launched in 1916, Pit & Quarry magazine serves the aggregates mining industry. Today, it offers its more than 23,000 readers informative articles on equipment and technology used by aggregates producers.</p> <p>First launched in 1996, Pit & Quarry's web site has become the leading online information source for aggregates producers. Using the latest technology, it provides visitors the most current and comprehensive information possible.</p>
 <p>www.quarrymanagement.com</p>	<p>Quarry Management magazine has been the official monthly Journal of The Institute of Quarrying for almost 90 years. Quarry Management's free weekly electronic Bulletin provides regular email updates on breaking news, new product launches, upcoming industry events and the very latest job opportunities within the sector.</p>
 <p>www.rocktoroad.com</p>	<p>Aggregates and Roadbuilding Magazine serves the aggregate and roadbuilding industry by providing readers with up-to-date news and information, features on aggregate plants, case stories on quarry and highway construction operations, in-depth coverage on vital topics affecting the industry including taxation, land use, trucking and other regulatory issues, updates on new products and equipment and maintenance tips as well as personnel changes, manufacturer / supplier news, convention / trade show coverage and other items of interest to aggregate producers and roadbuilding contractors.</p>
 <p>www.aggreatresearch.com</p>	<p>In 1999, the world's foremost experts in aggregate production, research and specification came together to form a unique technical resource called Aggregate Research Industries (ARI). They regard themselves as the world's foremost experts in manufactured sand.</p>
 <p>www.focusonaggregates.com</p>	<p>FocusOn Aggregates is a on-line edition providing several reviews on a number of exciting new products for the aggregate industry. The web-site provides reviews, videos and brochures of new products.</p>

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