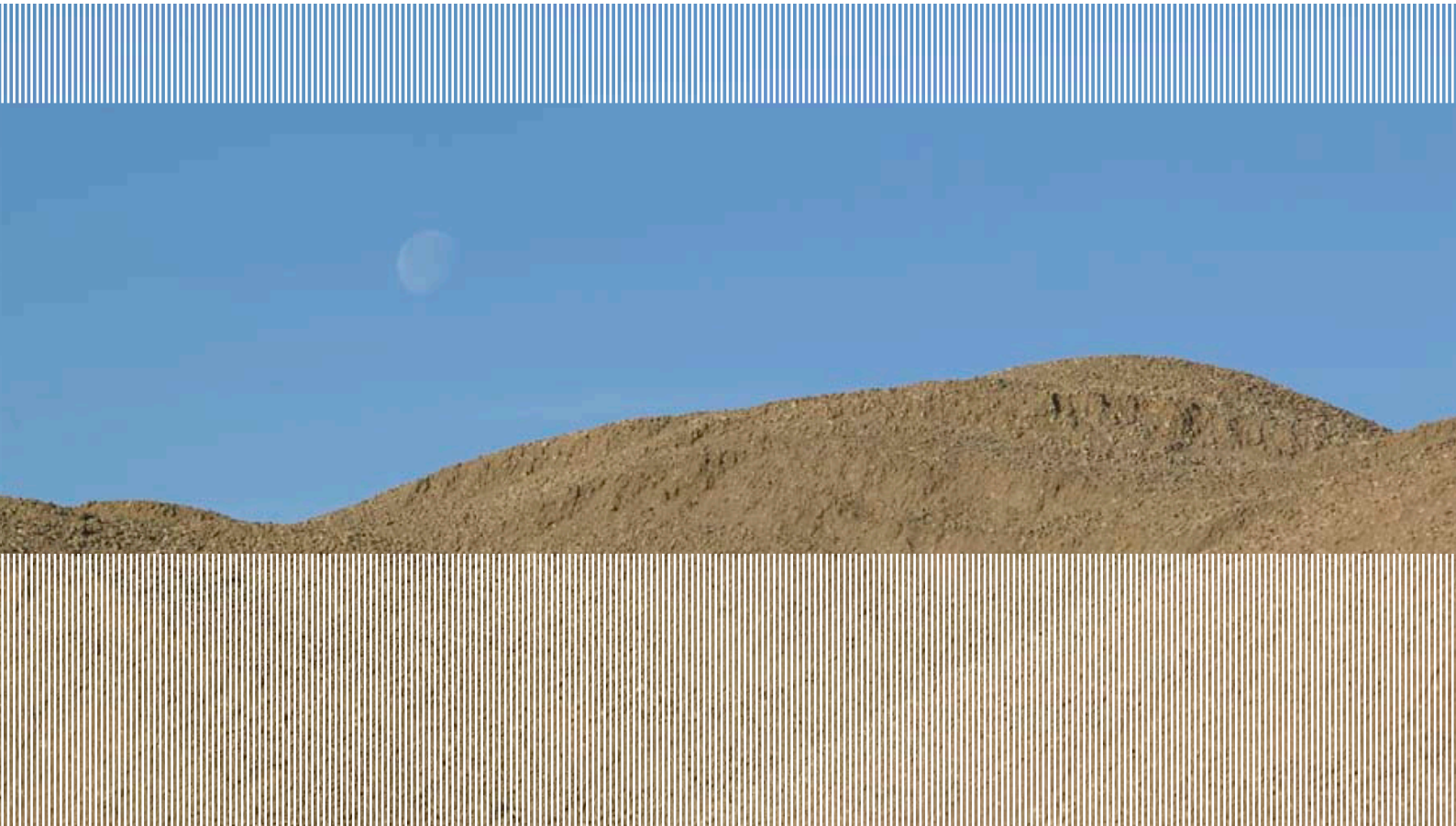


SINTEF Building and Infrastructure Bård Pedersen (NorStone)

Manufactured sand in concrete – effect of particle shape on workability

COIN Project report 34 – 2011



SINTEF Building and Infrastructure

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FA 2 Competitive constructions

SP 2.3 High quality manufactured sand for concrete

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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

The main objective of this study was to investigate how the particle shape of the fine aggregate affects the rheological properties of concrete. The work was carried out on mortar; or technically more correct on “mini concrete” with 8 mm maximum aggregate size.

Materials with a range from very poor to very good with respect to particle shape were chosen for the study. Each material was sieved into fractions 0.125/2 mm, 2/5 mm and 5/8 mm. Standardized filler was used to eliminate the filler effect. Three different qualities of crushed materials were sampled from the Tau production plant, among these two intermediate qualities with relatively poor particle shape. In addition, crushed materials from the quarries of Jelsa and Hokksund were included in the study. Årdal NSBR natural aggregate from the Årdal quarry was reference in this study.

The fresh properties were quantified by the use of slump and slump flow on a flow table also allowing the use of “dumps” to simulate the effect of vibration. The shape of the 2/5 and 5/8 mm fractions were quantified by use of standardized flakiness index (FI). The 0/2 fractions were characterised by use of the NZ flow cone.

In this study, mini-concrete with w/c ratio of 0.44 and 511 kg cement per m³ were used. In leaner mixes with larger aggregate size and higher w/c ratios the effects may be somewhat different. However, based on the given mix design in this study we may draw the following conclusions:

- For the fractions 2/5 mm and 5/8 mm the particle shape seems to have relatively little influence on the workability. Aggregate with flakiness index around 15-20 are performing nearly as well as particles from natural aggregate. Even particles with really poor shape (FI up to 50) seem to give relatively small negative influence on the workability. One reason for the relatively small effect of particle shape for these fractions is the relatively low amount of these fractions (20 volume %).
- The 0.125/2 mm fraction seems to have a much higher impact on the workability than the larger sized fractions. The span in slump achieved only by exchanging these fractions was 170 mm, which represents approximately 15-20 % in water and cement demand.
- The effect of VSI crushing for the Tau material is very large. While the Tau-material after 3 steps of gyratory crushing has a rather poor performance, a final step of VSI crushing gives significantly better performance. Hence, there may be a very large potential for shaping the particles < 2 mm size by the use of a VSI crusher.
- The NZ flow cone gives useful information on the performance of the 0/2 fraction. To some extent the performance in fresh concrete seems to be correlated to the flow cone results. However, there is a need for further work on the flow cone to learn how to evaluate these results.

The study presented here has illustrated that the main focus should be on the 0/2 fraction due to its large relative effect on the fresh properties. It seems obvious that VSI crushing is a very useful tool to improve the particle shape for the 0/2 fraction. However, there is a potential to optimize the use of VSI in order to get the best possible effect on the 0/2 fraction. Full scale testing using different VSI setups should preferably be done.

There is an obvious need for a reliable characterisation method for 0/2 materials. The NZ flow cone is an interesting approach. It should be further investigated in relation to the performances of a variety of natural and crushed Norwegian materials.

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1 Introduction

1.1 Principal objectives and scope

The main objective of this study was to investigate how different characteristics of the fine aggregates affect the rheological properties of concrete. The major part of the study was to investigate the effect of the **particle shape**.

The work was carried out on mortar; or technically more correct on “mini concrete” with 8 mm maximum aggregate size.

The study was divided into two parts:

- a) Effect of particle shape (standardized filler was used to eliminate the filler-effect)
- b) Testing of different sands (effect of filler included)

1.2 Background

As described in the State-of-the-art report by Wigum et al /1/, there is an increasing imbalance between the need for aggregates in the society and the available geological sources traditionally used for concrete. Some of the glaciofluvial deposits in Norway best suited for concrete purposes have an expected lifetime of less than 10 years. There will still be available natural aggregates for some decades in Norway, but much of the remaining resources available for exploitation have unsuitable locations in relation to the markets in the most densely populated areas. Consequently, there is an obvious need to switch the use from natural aggregate to crushed aggregate.

The use of **coarse** crushed aggregate in concrete is in most cases straight-forward, unless the shape of the coarse aggregate is very poor. Coarse crushed aggregate is widely used in combination with natural sand.

For the fine part of the aggregate (< 4 mm)¹ it is a lot more challenging to use crushed or manufactured materials. Many concrete producers have found that the use of mass fractions from 10 and up to 50 % may give rather good fresh concrete properties. But the final step – to use 100 % manufactured² sand is really challenging unless very high water and cement levels are used.

Manufactured sand is generally different from natural sand as discussed below:

- The particles are generally not as cubical, or at least not as rounded as natural aggregates. However, by the right setup of the crushing plant it is possible to produce aggregates with excellent shape. The use of VSI crushers is often, but not always, needed to obtain good shape.
- The fines content is generally higher in manufactured sand compared to natural sand. Generally speaking, the more effort being made to produce particles of good shape, the higher the fines content gets. Normally, the fines content has to be reduced either by dry or wet processing (air classification or washing) in order to become suitable for concrete purposes.

¹ According to NS-EN 12620 aggregates with $D < 4$ mm are classified as fine aggregate. However, due to the Norwegian traditional use of naturally graded 0/8, fractions < 8 mm are often referred to as “sand” while fractions > 8 mm are referred to as “stone”.

² In this report the terms “crushed” and “manufactured” sand/aggregate are used interchangeably.

- The particle size distribution is generally “dense” (towards Füller curve), while the grading of a typical Norwegian natural sand is straight or very often S-shaped. The grading curve of manufactured sand needs to be taken into consideration when it comes to mix design of concrete.

In addition, there are also some other differences. Manufactured sand produced from hard rock has generally lower variation in mineralogy, and the surfaces are less weathered than natural sand.

The study described in this report has focused on particle shape. Materials with shape from very poor to very good have been tested in “mini concretes” in order to quantify the relative influence of particle shape on workability. The materials were sieved in the following fraction: 0.125/2 mm, 2/5mm and 5/8 mm. The idea behind the study was to gain information about the relative influence of shape from each of these three fractions.

The study has been carried out within Project 2.3 Manufactured sand for concrete, one of 8 projects presently being carried out as part of COIN.

2 Methods and materials

2.1 Methods used in this investigation

2.1.1 Characterisation of 0/2

The particle shape is normally characterized by the flakiness index, or alternatively the shape index. However, these methods are only standardized for particles down to 4 mm nominal particle size. Hence, there is a need to develop characterisation methods for the finest part of the aggregate. One promising way of characterising the fine aggregate is to use the New Zealand (NZ) Flow Cone test /2/. This is a very simple method where dry sand runs through a cone into a receiver. The equipment is shown in Figure 1.



Figure 1 NZ Flow Cone (From Goldsworthy /2/).

Two parameters are recorded:

- The time for the sand to pass the flow cone.
- The loose density

These parameters are both related to the shape and texture of the particles. But obviously also the particle size distribution including the fines content is important. The fundamental aspects of this method are not yet fully understood, but the methodology gives a very good indication regarding performance of any given sand in concrete according to Goldsworthy /2/. Based on experience from New Zealand it was concluded that sands having characteristics that could fit within the envelope shown in Figure 2 performs well in concrete. This needs to be confirmed both for Norwegian natural and crushed sands.

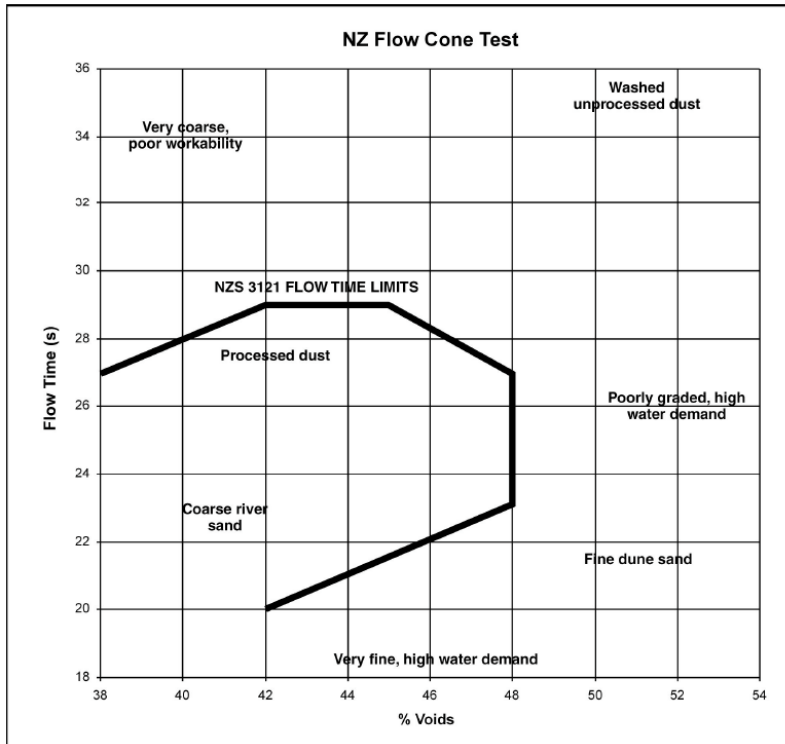


Figure 2 Flow Cone – prescribed envelope for good performance in concrete. From /2/.

While the original method prescribes the use of 0/4 mm sands, 0/2 mm sands were used in this study. The reason for this is that 4 mm sands with poor shape tend to block in the outlet of the cone. On the other hand, 2 mm sands having relatively poor shape flow well through the cone.

2.1.2 Workability of mini concrete

The mini concrete was mixed in a Hobart mixer as shown in Figure 3. The following mixing procedure was used:

- 0 min: start of dry mixing (cement and aggregates)
- 1 min: addition of water
- 2 min: addition of super plasticizer
- 3 min: stop mixer (1 minute rest)
- 4 min: start mixer (2 minutes mixing)
- 6 min: stop mixer

Speed 2 was used except during the first minute (dry mixing) where speed 1 was used.



Figure 3 *Mixing of mini concrete using a Hobart mixer.*

The workability was characterised using the ordinary slump cone in combination with a flow table as shown in Figure 4. The ordinary slump was measured, followed by measurement of the slump flow, which is the average diameter. The measurements of slump and slump flow were repeated after 5 “dumps” on the flow table.



Figure 4 *Ordinary slump cone and flow table. Measurement of slump and slump flow. Repeated measurements after 5 “dumps”.*

2.2 Materials

2.2.1 Description of aggregates

In the following, short descriptions of rock types and production facilities are given.

Årdal NSBR (NorStone)

The Årdal aggregate is a natural granite/gneiss glaciofluvial and moraine aggregate, partly mixed with crushed overburden moraine rock. The Årdal NSBR aggregate is reference aggregate in most Norwegian concrete laboratories.

Tau (NorStone)

This aggregate is produced from a Quartz diorite rock (Mylonite) with very good mechanical properties (Los Angeles value of 10). The commercial fractions are used basically for asphalt and are produced by 3 steps of gyratory crushing followed by VSI crushing. The layout of the production plant is given in Figure 5.

To investigate the effect of particle shape, three different versions of the aggregate were sampled from the plant. For details about the production plant, please see the layout of the production plant given in Figure 5. The three versions are described below:

- 1) VSI crushed material (commercial quality) in the following fractions: 0/2 mm washed, 2/5 mm and 5/8 mm)
- 2) 3 step gyratory crushing: Sample was taken after the tertiary crushing step (**before crusher K7**) and sieved manually in the following fractions: 0.125/2 mm, 2/5 mm and 5/8 mm.
- 3) 2 steps gyratory crushing. Sample was taken from 0/11 material taken **after sieve S1**, which was then sieved manually in the fractions 0.125/2 mm, 2/5 mm and 5/8 mm.

The idea by making three different versions of the same rock type was to isolate the effect of particle shape to get a quantification of the pure effect of shape on properties of fresh concrete. The achieved flakiness indices measured on the different rock types and fractions are shown in Table 1.

Comments to products 2 and 3: Product 2 (3 step gyratory crushing) is never sold commercially; it is only an intermediate product. Product 3 (2 step gyratory crushing) is never used for concrete, but is mixed with coarser fractions and sold as “sub-base material” to the construction industry.

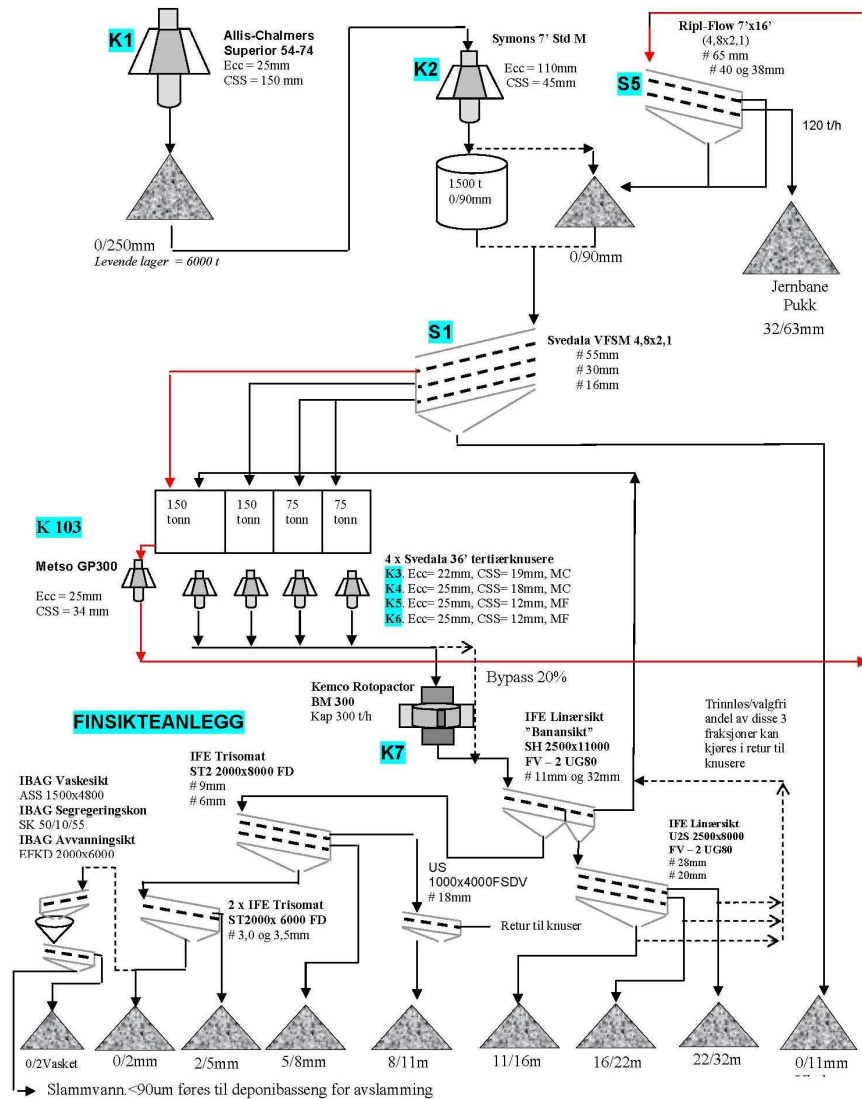


Figure 5 Layout of the Tau production plant

Jelsa (Norsk Stein)

The dominating rock type in this quarry is Granodiorite. The production process includes primary jaw crushing followed by 4 steps of gyratory crushing. Samples of the commercial products 0/2 mm “normal washed”, 0/2 mm “hard washed”, 2/5 mm and 5/8 mm were used for this investigation. The production plant of Jelsa is described in more detail in the report of Danielsen /3/.

Hokksund (Kolo Veidekke)

The dominating rock type in this quarry is gneiss diorite. The aggregate is produced in three crushing steps. No facilities for filler reduction are presently available. A detailed description of the production facilities is given by Wigum /4/. A sample of 0/4 was used for the present investigation.

An overview of the flakiness indices of the different fractions are given in Table 1. The flakiness index is a simple measure of the particle shape. It can be seen that the materials range from very good – low value (Årdal NSBR) to very poor – high value (Tau 2 step crushing). Flow Cone results for all 0/2 mm sands are also compiled in Table 1.

Table 1 Aggregate characteristic: Flow cone results (0/2 mm) and Flakiness index (2/5 and 5/8 mm)

Materials	Flow cone				Flakiness index (FI)	
	0/2 mm		0/2 mm without filler		2/5 mm	5/8 mm
	Flow time	Void %	Flow time	Void %	(4/5)	
Tau VSI crushing	29.0	46.4	29.1	47.9	19	15
Tau 3 step crushing	not flowing	not flowing	31.3	49.6	36	34
Tau 2 step crushing	not flowing	not flowing	30.1	49.1	50	47
Jelsa (normal washed 0/2)	29.3	46.3	-	-	13	11
Jelsa (hard washed 0/2)	28.6	47.7	29.1	48.1	13	11
Hokksund	35.8	45.6	30.8	48.3	27	-
Årdal NSBR	22.9	42.3	-	-	3	3

Grading curves for the sands are presented in *Figure 6*.

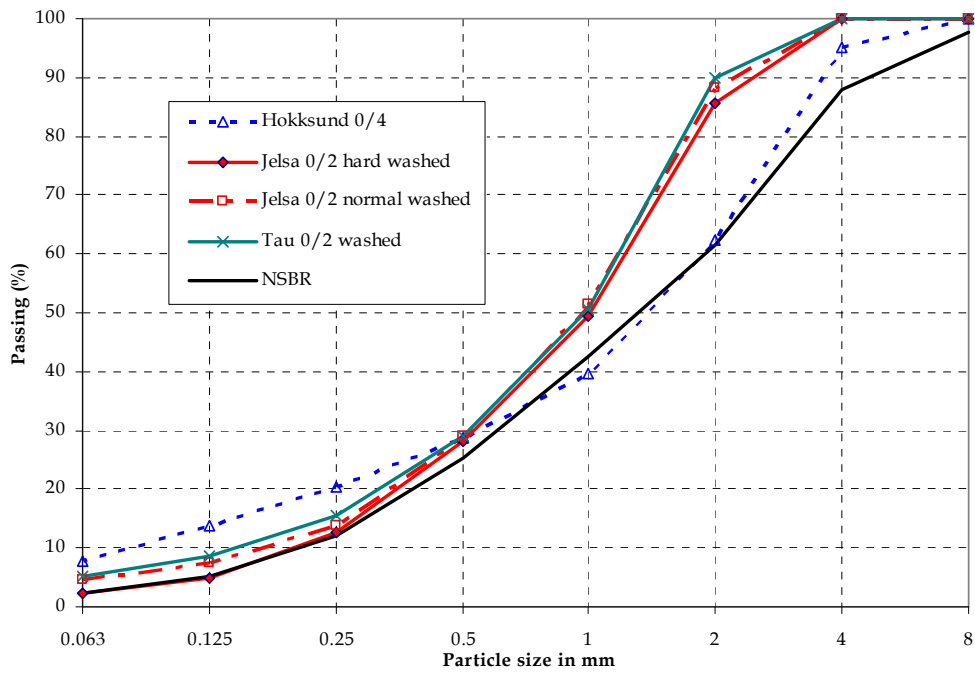


Figure 6 Grading curves of different sands

The particle size distributions of the fillers (0/0.125 mm) are given in Figure 7.

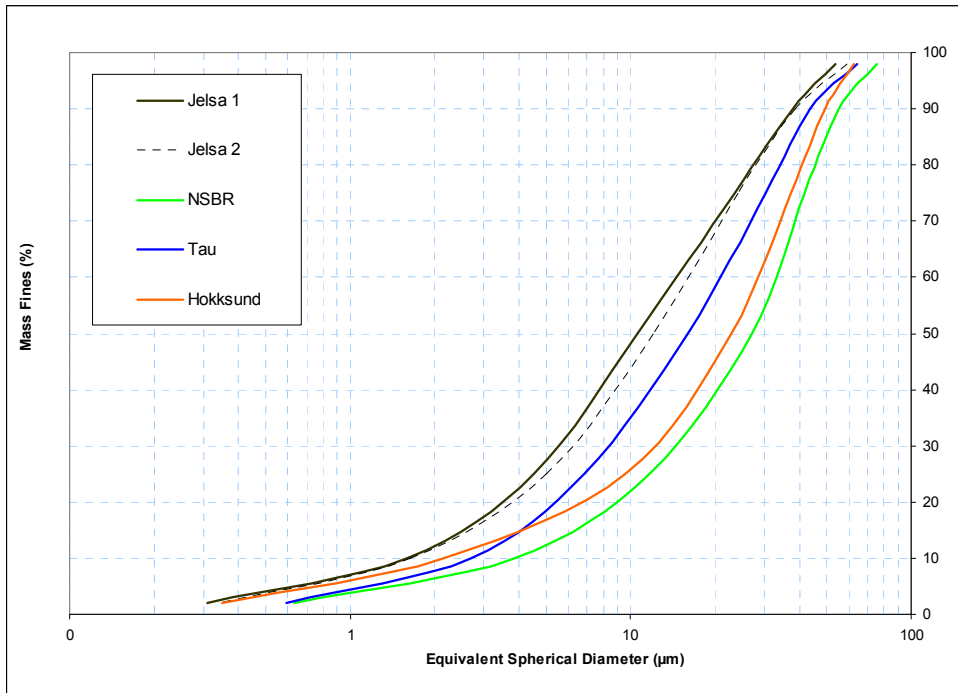


Figure 7 Sedigraph results of fillers. Results from Wigum /5/.

2.2.2 Other materials

Short descriptions of the cement and plasticizer are given below.

Cement:

Norcem Standardsement FA was used for all experiments. This cement is a CEM II/A-V 42.5 R with typical Blaine-value of 450 m²/kg.

Plasticizer:

Rescon Dynamon SX-N. This is a superplasticizer based on modified acrylic polymers. The solids content is 18.5 %.

2.3 Experimental programme

The following recipe was used for all mixes:

- Norcem Standard FA cement: 511 kg/m³
- Water 225 kg/m³
- w/c 0.44
- Rescon Dynamon SX-N 0.9 % of cement weight
- Aggregate 0/2 mm: 60 weight % of total aggregate
- Aggregate 2/5 mm: 20 weight % of total aggregate
- Aggregate 5/8 mm: 20 weight % of total aggregate

An overview of the parameter study on particle shape is shown in Table 2. Note that the effect of filler was eliminated by using standardized filler in all these experiments.

Table 2 (Series A). Parameter study: particle shape. Effect of filler eliminated by use of standardized filler.

Mix	Aggregate fractions		
	0.125/2 mm	2/5 mm	5/8 mm
A1	Tau VSI washed	Tau VSI	Årdal
A2	Tau VSI washed	Tau VSI	Tau VSI
A3	Tau VSI washed	Tau VSI	Tau 3 step
A4	Tau VSI washed	Tau VSI	Tau 2 step
A5	Tau VSI washed	Tau VSI	Jelsa
B1	Tau VSI washed	Årdal	Tau VSI
B2	Tau VSI washed	Tau 3 step	Tau VSI
B3	Tau VSI washed	Tau 2 step	Tau VSI
B4	Tau VSI washed	Jelsa	Tau VSI
C1	Årdal*	Tau VSI	Tau VSI
C2	Tau 3 step*	Tau VSI	Tau VSI
C3	Tau 2 step*	Tau VSI	Tau VSI
C4	Jelsa*	Tau VSI	Tau VSI

* Reference filler from Tau commercial washed in all mixes.

In addition to the parameter study according to Table 2, a limited study also including the effect of the filler of each aggregate type was carried out. The test program is shown in Table 3.

Table 3 (Series B). Test of materials included filler.

Mix	Aggregate fractions		
	0/2 mm	2/5 mm	5/8 mm
D1 (A2)	Tau VSI washed	Tau VSI	Tau VSI
D2	Jelsa normal washed	Jelsa	Jelsa
D3	Jelsa hard washed	Jelsa	Jelsa
D4	Hokksund	Hokksund	Tau VSI
D5	NSBR	NSBR	NSBR

3 Results

3.1 Presentation of results

A compilation of the test results (slump and flow) are given in Table 4 and Table 5. Discussion are presented in Section 4; Discussions.

Table 4 Results of series A; (effect of filler excluded by using Tau reference filler in all mixes)

Mix	Aggregate fractions			Slump and flow results			
	0.125/2 mm	2/5 mm	5/8 mm	Slump (mm)	Flow (mm)	Slump ^{5*} (mm)	Flow ^{5*} (mm)
A1	Tau VSI w.	Tau VSI	Årdal	210	380	260	450
A2	Tau VSI w.	Tau VSI	Tau VSI	200	360	240	430
A3	Tau VSI w.	Tau VSI	Tau 3 step	170	305	230	370
A4	Tau VSI w.	Tau VSI	Tau 2 step	180	305	230	365
A5	Tau VSI w.	Tau VSI	Jelsa	210	365	250	435
B1	Tau VSI w.	Årdal	Tau VSI	230	410	250	450
B2	Tau VSI w.	Tau 3 step	Tau VSI	200	335	240	400
B3	Tau VSI w.	Tau 2 step	Tau VSI	190	310	240	380
B4	Tau VSI w.	Jelsa	Tau VSI	230	430	250	465
C1	Årdal*	Tau VSI	Tau VSI	250	465	280	545
C2	Tau 3 step*	Tau VSI	Tau VSI	100	200	170	295
C3	Tau 2 step*	Tau VSI	Tau VSI	80	200	150	265
C4	Jelsa*	Tau VSI	Tau VSI	210	370	250	435

* Reference filler “Tau VSI washed” in all mixes.

^{5x} After 5 “dumps”

Table 5 Results of series B (effect of filler included).

Mix	Aggregate fractions			Slump and flow results			
	0/2 mm	2/5 mm	5/8 mm	Slump (mm)	Flow (mm)	Slump ^{5*} (mm)	Flow ^{5*} (mm)
D1 (A2)	Tau VSI	Tau VSI	Tau VSI	200	360	240	430
D2	Jelsa norm. w.	Jelsa	Jelsa	240	435	260	520
D3	Jelsa hard w.	Jelsa	Jelsa	230	400	260	465
D4	Hokksund	Hokksund	Tau VSI	170	290	230	370
D5	Årdal	Årdal	Årdal	250	460	270	550

^{5x} After 5 “dumps”

4 Discussions

4.1 Introduction

In the following sections the most important results are presented, followed by brief discussions.

4.2 Effect of particle shape (series A)

The effects of workability caused by the different 5/8 mm fractions are shown in Figure 8 and Figure 9. As expected due to the excellent particle shape, the Årdal aggregate gives highest slump and flow. On the other hand, the Tau materials being crushed in 2 or 3 steps results in the lowest workability in terms of slump and flow. The differences in flow properties relate relatively well to the measured flakiness indices as presented in Table 1. Higher flakiness index (poorer shape) generally results in lower slump and flow. However, there is hardly any significant difference in workability properties between the Tau materials crushed in 2 and 3 steps respectively. Also note that there was no significant difference between the Årdal material which is a natural aggregate and the Jelsa aggregate which is crushed.

Based on the relatively large spectre in particle shape as can be seen in Table 1, the differences were expected to be somewhat higher. But the relatively low amount of 5/8 mm (20 %) which corresponds well to daily practice, may explain the relatively low differences.

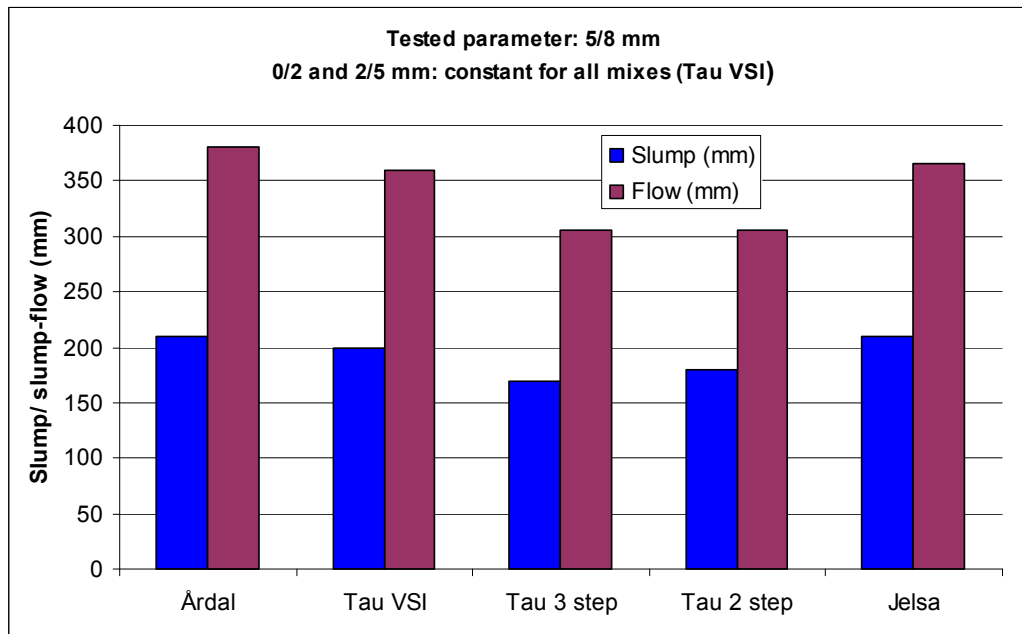


Figure 8 Effect of 5/8 mm fraction on workability of concrete.

The maximum difference in slump was 40 mm (Årdal versus Tau 3 step). Based on previous practical experience it may be estimated that an extra addition of 2.5 – 3 litres of water per m³ per cm is needed for the Tau step 3 mix to reach the same level of slump. This means that 10 – 12 litres of extra water are needed, corresponding to 22 – 27 kg increased cement level or approximately 5 % increased cement content.

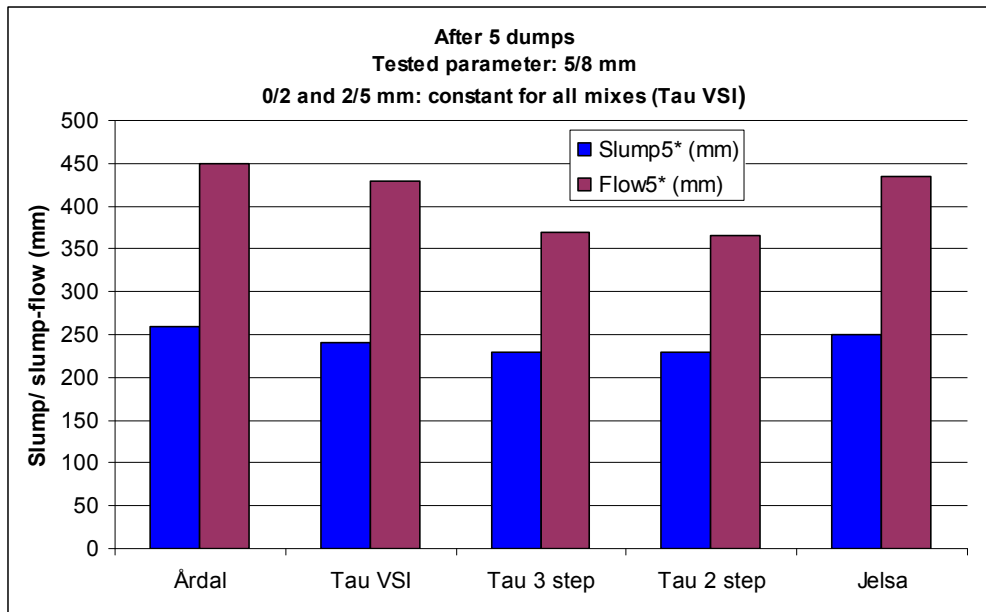


Figure 9 Effect of 5/8 mm fraction on workability of concrete. Results after 5 dumps.

The effects on workability caused by exchanging the 2/5 mm fractions can be seen in Figure 10 and Figure 11. Årdal and Jelsa give equal workability. Generally, the differences are relatively small, and in the same order as for the 5/8 mm fractions. In particular, the differences after 5 dumps, which are believed to give a relatively good indication on flow properties in a real casting situation, seem to be small. Note that Jelsa aggregate gave even better workability results than Årdal even though the shape is significantly poorer.

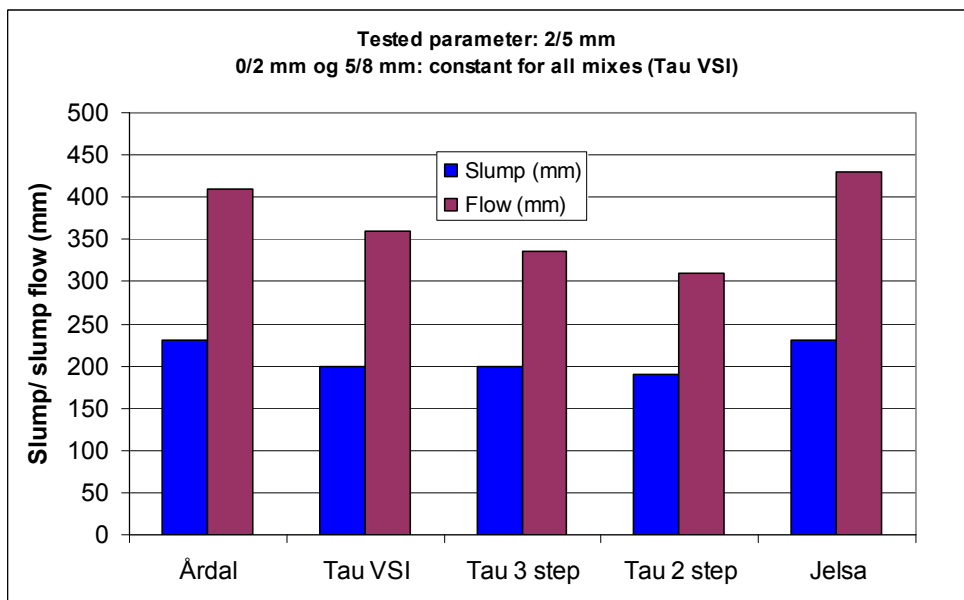


Figure 10 Effect of 2/5 mm fraction on workability of concrete.

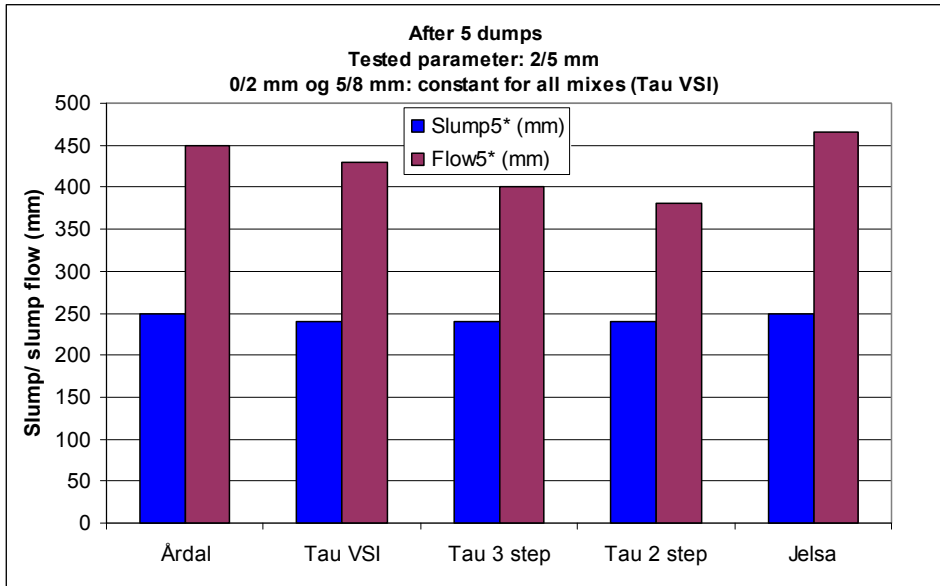


Figure 11 Effect of 2/5 mm fraction on workability of concrete. Results after 5 dumps.

In Figure 12 and Figure 13, the effects of exchanging the 0.125/2 mm fractions can be seen. As expected, the Årdal natural sand is best in terms of workability, and the Tau material crushed in 2 steps is worst.

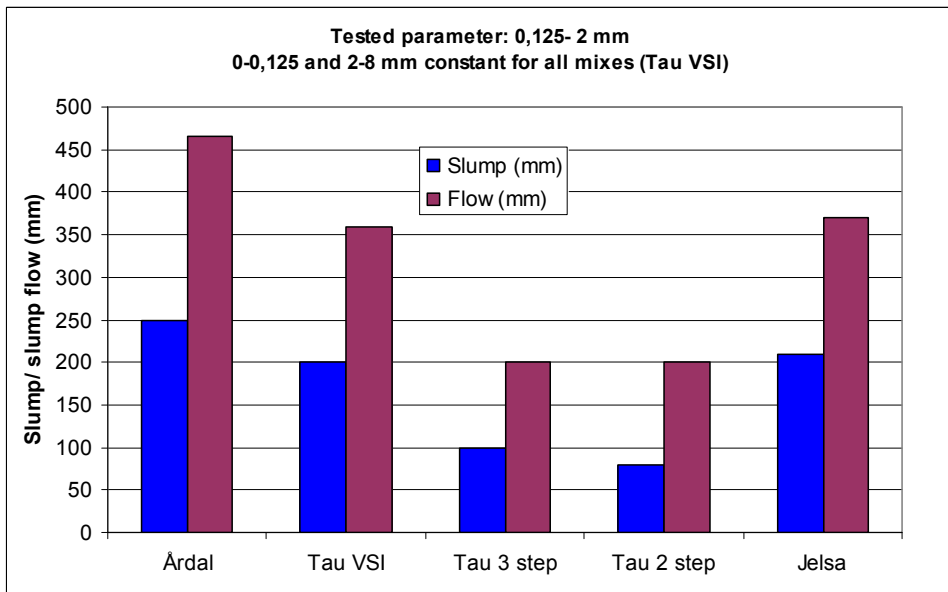


Figure 12 Effect of 0.125/2 mm fraction on workability.

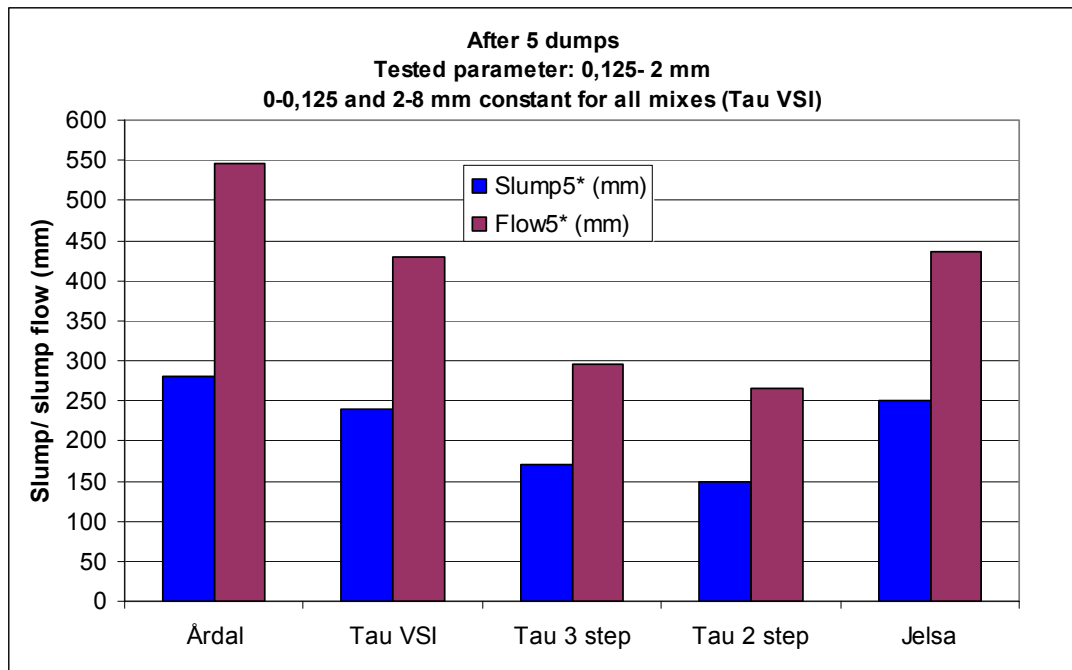


Figure 13 Effect of 0.125/2 mm fraction on workability. Results after 5 dumps.

Both the Tau VSI as well as the Jelsa material perform rather well. However, the difference in workability is 40-50 mm compared to the mix with Årdal 0.125/2 mm. Based on experience it is believed that this difference represents difference of approximately 25-30 kg cement per m³, or approximately 5-6 %.

For the poorest qualities of Tau, 2 and 3 step crushing, there is a slump difference of 150 mm or more up to the best mix with Årdal fine aggregate. To compensate for this difference only by increasing water and cement, we can assume an increase in water and cement demand in the order of 15-20 %.

We can conclude that the effect of the 0.125/2 mm fraction is significantly larger than the effects of the 2/5 mm and 5/8 mm fraction. Thus, we may conclude that the finest fraction is the most important, and therefore needs the biggest attention. One obvious reason for the large effect from this particular fraction is that the volume fraction of 0.125/2 mm is 3 times higher than the other fractions (60 % versus 20 %).

There are no standardized methods to quantify the shape of the 0/2 fraction. In this study, the NZ flow cone was used as an indirect measure of the particle shape. The flow cone results are discussed in Section 4.4.

4.3 Effect of sand types included filler effect (series B)

The results of series B are compiled in Table 5 and are presented graphically in Figure 14 and Figure 15. Note that these results represent the potential of the full 0/8 mm curves for each material – including the effect of the filler.

The total span in slump for these materials goes from 170 (Hokksund) to 250 (Årdal). To compensate for this slump difference only by adding water and cement we can assume that there is a need for approximately 40-45 kg of extra cement, which is approximately 8 %.

The Jelsa material seems to give a remarkably high workability, in the same order as the Årdal reference. In particular, the “normal washed” version of 0/2 mm seem to be very well suited for concrete.

It should be noted that the filler content within the Hokksund material has not been reduced after the crushing, while the Tau and Jelsa materials have been washed. As an example, the washing process at Tau removes approximately 70-75 % of the particles < 0.063 mm. The Tau and Jelsa materials which are directly from the crushing process with no washing are not very well suited for concrete, particularly not in cement-rich mixes as used in this study. However, in lean concrete mixes with significantly higher w/c ratios larger filler content may be beneficial.

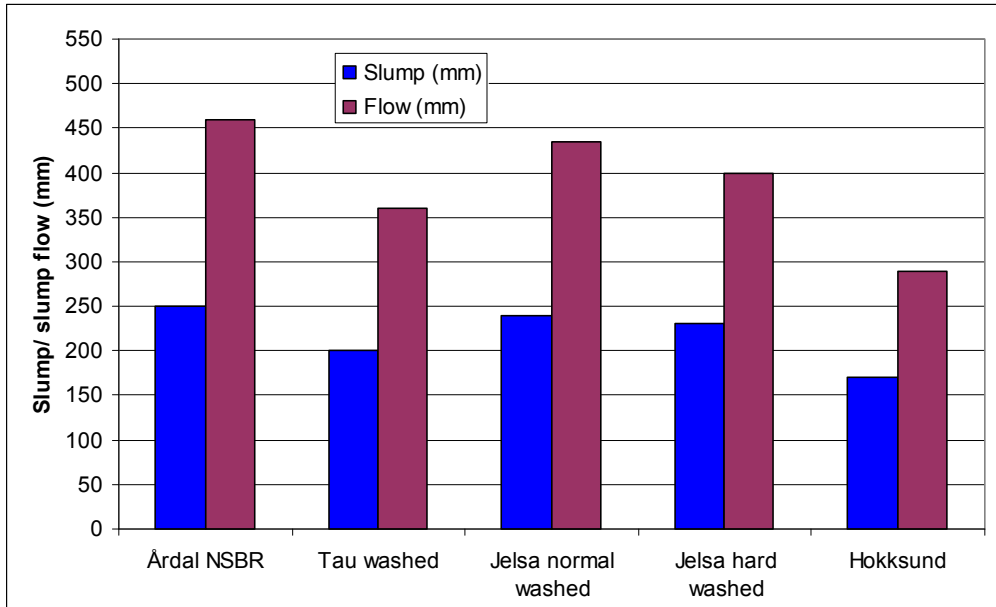


Figure 14 Effects of different sand types on workability. Effect of fillers included.

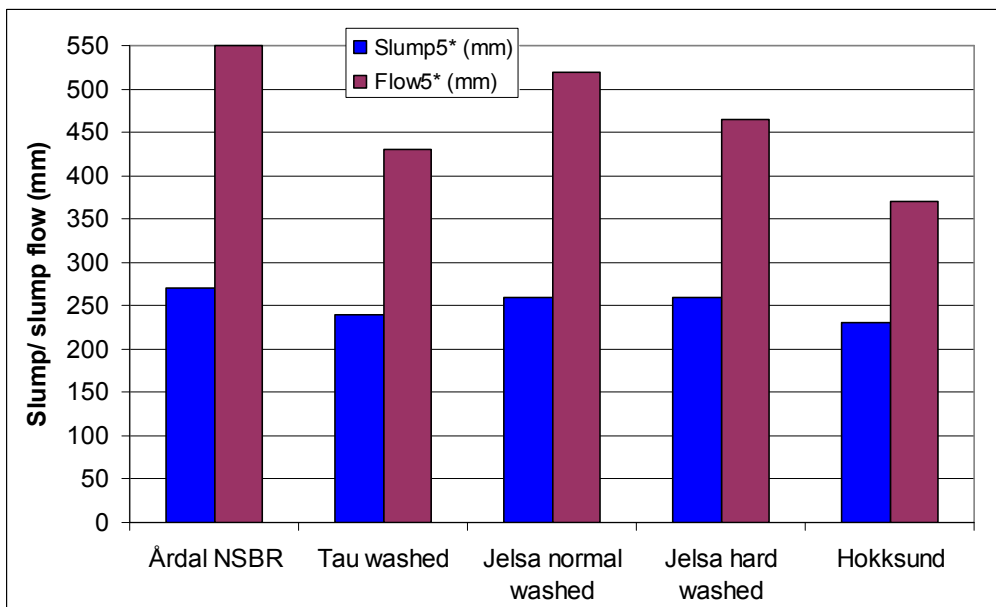


Figure 15 Effects of different sand types on workability. Effects of fillers included. Results after 5 “dumps”.

4.4 Flow cone as a quality measure of the 0/2 fraction

As a part of this study, all 0/2 mm materials were tested by using the NZ flow cone. All flow cone results are shown in Table 1 and plotted in Figure 15.

Note that only the Årdal 0/2 mm falls inside the NZ envelope, while all the other results are outside. However, the materials with best performance with respect to workability (Tau VSI and Jelsa) are rather close to the envelope. Based on NZ experience sands with flow cone results that fall inside this envelope perform well in concrete, while sands falling outside may have poorer performance with respect of fresh properties.

There is a clear effect from the filler content, which can be seen in Figure 15. In particular, there is a large decrease in flow time for the Hokksund material if the filler is removed. Also for the Tau VSI material the filler content seems to have an impact. But in this case the impact is only on the loose packing density which is higher when the filler is included. This effect on the increased packing density of the filler material is expected as the filler particles fill the space between the larger particles.

The treatment of filler is an obvious problem with this method. The procedure of the method says:

“If the percentage passing 0.075 mm test sieve is greater than 7 %, wash sample over a 0.075 mm test sieve and oven dry to constant mass”.

According to this, the correct test results of the Hokksund material is the one without filler, since the amount passing 0.075 mm is > 7 %. For the Tau VSI material on the other hand, the correct result is the one with filler included.

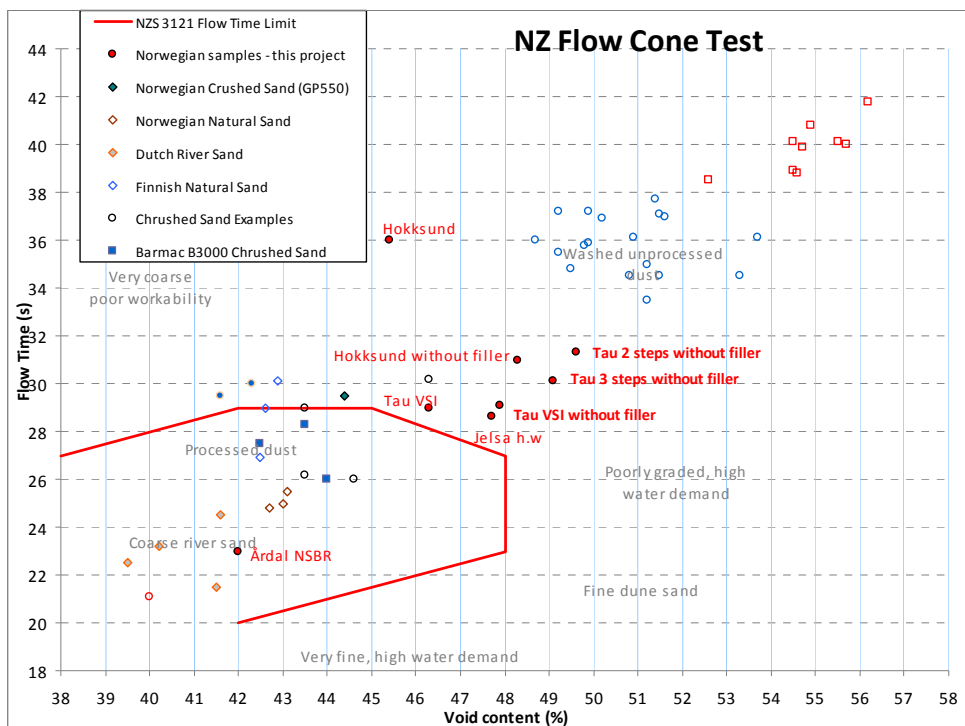


Figure 15 Flow cone results for the tested 0/2 materials.

5 Conclusions and recommendations for further work

5.1 Limitations of the study

In the study presented in this report, we have used only one standard recipe with w/c of 0.44. The maximum particle size was 8 mm. As a consequence of this, the cement content was relatively high (511 kg/m³). We know from practical experience that the relative effects of aggregates are dependent on the concrete mix design including w/c ratio, choice of cement, choice of plasticizer, particle size distribution of the aggregate as well as the maximum particle size of the aggregate. Hence, the results presented in this report are only 100 % valid for the exact mix design used in this study. We should therefore be careful about the conclusions.

We should also keep in mind that the tests used in this study (slump and flow, including flow table) does not give the full information about properties related to form filling and surface finishing, they only give indications about the properties we could expect in a real casting situation. Further work on this topic should preferably include full scale casting of concrete.

5.2 Conclusions

Having the limitations in mind, we can draw some conclusions.

- For the fractions 2/5 mm and 5/8 mm the particle shape seems to have relatively little influence on the workability compared to the 0/2 mm fraction. Aggregate with flakiness index around 15-20 are performing nearly as well as particles from natural aggregate. Even particles with really poor shape (FI up to 50) seem to give relatively small negative influence on the workability. One reason for the relatively small effect of these fractions is the relatively low amount (20 %) of each of these fractions.
- The 0.125/2 mm fraction seems to have a much higher impact on the workability than the larger sized fractions. The span in slump achieved only by exchanging these fractions was 170 mm, which represents approximately 15-20 % variation in water and cement demand.
- The effect of VSI crushing for the Tau material is very large. While the Tau-material after 3 steps of gyratory crushing has a rather poor performance, a final step of VSI crushing gives significantly better performance. Hence, there is a very large potential of shaping the particles < 2 mm size by the use of a VSI crusher. It should be noted that the VSI process being used at the Tau plant is not optimized for shaping the minus 2 mm particles, but rather to increase the shape of the 5/8 mm and 8/11 mm fractions.
- When the full curve of each material, including filler, is tested it is obvious that materials from Tau, Jelsa and Hokksund have a potential for use in concrete as they are. In particular, this seems to be the case for the Jelsa material which performs excellent even compared to the Årdal reference. The Hokksund material has the poorest performance among the tested materials, most likely due to the very simple process without VSI and without any filler reduction.
- The NZ flow cone gives useful information about the performance of the 0/2 mm fraction. To some extent the performance in fresh concrete seems to be correlated to the flow cone results. However, there is a need for further work on the flow cone to learn how to evaluate these results.

5.3 Recommendations for further work

The study presented here has illustrated that the main focus should be on the 0/2 mm fraction due to its large relative effect on the fresh properties. It seems obvious that VSI crushing is a very useful tool to improve the particle shape for the 0/2 mm fraction. However, there is a potential to optimize the use of VSI in order to get the best possible effect on the 0/2 mm fraction. Full scale testing using different VSI setups should preferably be done.

There is an obvious need for a reliable characterisation method for 0/2 mm materials. The NZ flow cone is an interesting approach. It should be further investigated in relation to the performances of a variety of natural and crushed Norwegian materials.

In this study we focused on the particle shape, and not on the filler content and the characteristics of the different fillers. However, there is a need for further studies on the effect of fillers in combination with the other concrete constituents. This knowledge is crucial for further development of mix-design technology for use of 100 % manufactured aggregates.

6 Acknowledgements

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