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Utilization of Rock Materials from Tunnelling as Aggregates for Sprayed Concrete

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TITLE:

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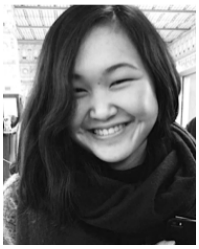
Bruk av tunnelmasser som tilslag i sprøytebetong

BY:

Judy Yuen Wah Luong



SUMMARY:

The concrete industry in Norway, as well as other countries, is facing a great challenge nowadays. The enormous increase in demand for concrete production and the consequential increase in aggregate consumption have resulted in shortage of natural aggregate resources, especially in terms of suitable materials for concrete production. While the good natural aggregate resources in Norway are reducing in volume and number, great amounts of crushed masses are generated from tunnelling projects and transported over long distances to be deposited in sea and landfills. Crushed aggregates tend to have less beneficial properties with respect to concrete workability than natural aggregates, in the sense that these aggregates tend to have a higher fines content and a higher content of irregularly shaped particles. This explains why rock materials from tunnelling is not much exploited and why more research on this area is important.

In this study, the possibility of using crushed rock materials from tunnelling as aggregates in sprayed concrete has been evaluated. Crushed sand materials from two ongoing tunnelling projects, the Ulriken tunnel and the Follo Line tunnel, have been investigated and compared with a conventional natural sand. The evaluation has been based on their performance in fresh concrete. To better understand the relationship between aggregate properties and fresh concrete properties, the particle-matrix model has been implemented. In this material model, fresh concrete is considered as a two-phase system, consisting of a liquid part, the matrix phase, and a friction part, the particle phase.

The geometrical properties, that is, the grading, the fines content, the particle shape and the free mica content, of each sand material were characterized. Four concrete mixes, one with pure natural sand, two with combined natural/crushed sand and one with pure crushed sand, were studied. The properties of the particle phase and the matrix phase of each concrete mix were characterized by means of the void content test and the FlowCyl test, respectively. Finally, the rheological properties, the slump, the slump-flow, the yield shear stress and the plastic viscosity, of each concrete mix were characterized.

The results of this study have revealed that the geometrical properties of aggregates influence mainly the plastic viscosity of fresh concrete and to a lesser extent the yield stress, the slump and the slump-flow for a 200-mm-slump concrete. The results indicate that the plastic viscosity of a *matrix* dominated concrete mix,

which is achieved with a low void content and a high matrix volume, is predominantly governed by the free mica content and the content of fine particles, whereas the plastic viscosity of a *particle* dominated concrete mix is mainly affected by the particle shape quality.

The results have demonstrated that up to 50 % of natural sand in sprayed concrete can be replaced with crushed rock materials from tunnelling, provided that the free mica content is not too high and the content of fines is kept at an acceptable level with respect to both stability and rheology of fresh concrete. Such replacement is possible even for crushed rock materials with a high content of irregularly shaped particles. This is because the effect of particle shape quality on fresh concrete properties is somewhat reduced for sprayed concrete, as this type of concrete typically is proportioned with a high matrix volume. However, the effect of particle shape quality increases with increasing content of irregularly shaped particles. Hence, replacing all natural sand with crushed rock materials from tunnelling will be unreasonable technically, economically and environmentally, unless dedicated efforts are made to improve the particle shape quality.

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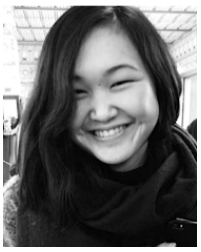

SAMMENDRAG:

Betongindustrien i Norge og en rekke andre land står overfor en stor utfordring i dag. Den enorme økningen i betongproduksjon og den tilhørende økningen i bruk av tilslag har ført til mangel på gode naturlige tilslagsforekomster. Mens de naturlige tilslagsforekomstene reduseres i volum og antall, blir det årlig produsert store mengder knuste masser fra tunnelprosjekter, som blir transportert over store avstander for å bli deponert. Knust tilslag har ofte mindre fordelaktige egenskaper for betongstøpeligheten, ettersom det ofte har et høyere innhold av finstoff og kantede korn. Dette forklarer hvorfor knust masser fra tunnelprosjekter fortsatt er lite utnyttet, og hvorfor det er så viktig å gjøre forskning i dette området.

Bruk av knust tunnelmasse som tilslag i sprøytebetong har blitt evaluert i denne studien. Knust sand fra to pågående tunnelprosjekter, den nye Ulriken-tunnelen og Follobanen, har blitt undersøkt og sammenlignet med et naturlig tilslag som er mye brukt i betong. Evalueringen har tatt utgangspunkt i deres effekt på betongstøpeligheten. For å bedre forstå forholdet mellom egenskapene til tilslag og støpeligheten til betong, har partikkel-matriks-modellen blitt tatt i bruk. I denne modellen, blir den ferske betongen betraktet som et to-komponentmateriale, bestående av en flytende del, matriksfasen, og en friksjonsdel, partikkelfasen.

De geometriske egenskapene, med andre ord graderingen, finstoffinnholdet, kornformen og glimmer-innholdet, har blitt karakterisert for hvert tilslag. Fire betongblandinger, én med ren naturlig sand, to med kombinert naturlig/knust sand og én med ren knust sand, har blitt undersøkt. Egenskapene til partikkelfasen og matriksfasen har blitt karakterisert for hver betongblanding ved hjelp av henholdsvis hulromstesten og FlowCyl-testen. Til slutt har de reologiske egenskapene, med andre ord synkmålet, synkutbredelsesmålet, flyteskjær-spenningen og den plastiske viskositet, blitt karakterisert for hver betongblanding.

Resultatene av denne studien har vist at de geometriske egenskapene hovedsakelig påvirker den plastiske viskositeten og i mindre grad synkmålet, synkutbredelsesmålet og flyteskjær-spenningen for en 200-mm-synk betong. Resultatene har også vist at den plastiske viskositeten til en matriksdominert betongblanding, som oppnås med et lavt hulromsinnhold og et høyt matriksvolum, hovedsakelig påvirkes av glimmerinnholdet og finstoffinnholdet, mens den plastiske viskositeten av en partikkeldominert betongblanding hovedsakelig påvirkes av kornformen.

Resultatene indikerer at opptil 50 % av den naturlige sanden i sprøytebetong kan erstattes med knust tunnelmasse, forutsatt at glimmerinnholdet ikke er for høyt og at finstoffinnholdet holdes på et akseptabelt nivå i forhold til betongstabilitet og betongreologi. En slik erstatning er mulig selv for knust tunnelmasse med høyt innhold av kantede korn. Dette skyldes at kornformens kvalitet har mindre effekt på støpeligheten til sprøytebetong, da denne typen betong ofte har et høyt matriksvolum. Effekten øker imidlertid med et økende innhold av kantede korn. Å erstatte all naturlig sand med knust tunnelmasse vil derfor være urimelig teknisk-, økonomisk- og miljømessig sett, med mindre det gjøres tiltak for å bedre kornformens kvalitet.

FAGLÆRER: Klaartje De Weerdt

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UTFØRT VED: NTNU Trondheim

PREFACE

This master thesis terminates the author's master's degree program of Civil and Environmental Engineering at NTNU, with specialization in concrete technology. The thesis constitutes the course TKT 4925 Concrete Technology – Master Thesis that counts for 30 ECTS credits. The thesis was written in 20 weeks during the spring semester 2017 and is a continuation of the associated specialization project *Crushed Aggregates in Sprayed Concrete – Literature study,* written during the autumn semester 2016.

This master thesis has been initiated as a collaborative research work between the Department of Structural Engineering at the Norwegian University of Science and Technology (NTNU), the department of Architecture, Materials and Structures at SINTEF and the Norwegian Public Roads Administration (NPRA). The background for this collaboration is the on-going R&D project *Local materials* (*Kortreist stein*) of the Norwegian Research Council, for which Veidekke is the project owner.

The major part of the practical work associated to this master thesis has been carried out at the concrete laboratories of the Department of Structural Engineering at NTNU and the department of Architecture, Materials and Structures at SINTEF. Some of the practical work has taken place at the particle laboratory at the Department of Geoscience and Petroleum at NTNU.

The main supervisor has been Associate Professor Klaartje De Weerdt, NTNU, and the co-supervisors have been Senior Scientist Kari Aarstad, SINTEF, and Senior Principal Engineer Øyvind Bjøntegaard, NPRA.

Parallel to this master thesis, the author has during the spring semester 2017 taken the subject TKT 4215 Concrete Technology 1 that counts for 7.5 ECTS credits, participated in the course Sprayed concrete for Rock Support arranged by the Norwegian Concrete Association, and submitted a paper to the XXIIIth Symposium on Nordic Concrete Research & Development. The submitted paper can be found in the attachment. Previously taken subjects of relevance include TKT4235 Concrete Technology 2 (advance course) and TBA4150 Construction Engineering, both taken during the autumn semester 2016.

ACKNOWLEDGMENT

I would like to express my sincere gratitude to my main supervisor Klaartje De Weerdt and co-supervisors Kari Aarstad and Øyvind Bjøntegaard, for their valuable supervision throughout the process. I would especially like to express my appreciation to Klaartje De Weerdt for all the time she has spent on my work. Her engagement to my work has motivated me.

I would like to thank the staff at the SINTEF concrete laboratory: Knut Lervik, Roger Leistad and Erik Johansen for their participation in my experimental work and for their guidance and assistance at the laboratory, and Stig Roar Rudolfsen and Tore Stæhli for helping me out with some of the experiments. Additionally, I would like to thank Senior Research Scientist Marit Haugen (SINTEF) and Senior Engineer Irene Bragstad (SINTEF) for performing some of the experiments for me and for spending time answering my questions.

I would like to extend my appreciation to the staff at the NTNU concrete laboratory, especially Steinar Seehuus for his help with my experimental work. Finally, I would like to convey my thankfulness to Professor Sverre Smeplass (NTNU/Skanska) and Postdoctoral Fellow Rolands Cepuritis (NTNU/NorStone) for their guidance and for spending time answering my questions.

Trondheim, June 2017

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ABSTRACT

The concrete industry in Norway, as well as other countries, is facing a great challenge nowadays. The enormous increase in demand for concrete production and the consequential increase in aggregate consumption have resulted in shortage of natural aggregate resources, especially in terms of suitable materials for concrete production. While the good natural aggregate resources in Norway are reducing in volume and number, great amounts of crushed masses are generated from tunnelling projects and transported over long distances to be deposited in sea and landfills. Crushed aggregates tend to have less beneficial properties with respect to concrete workability than natural aggregates, in the sense that these aggregates tend to have a higher fines content and a higher content of irregularly shaped particles. This explains why rock materials from tunnelling is not much exploited and why more research on this area is important.

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The results of this study have revealed that the geometrical properties of aggregates influence mainly the plastic viscosity of fresh concrete and to a lesser extent the yield stress, the slump and the slump-flow for a 200-mm-slump concrete. The results indicate that the plastic viscosity of a *matrix* dominated concrete mix, which is achieved with a low void content and a high matrix volume, is predominantly governed by the free mica content and the content of fine particles, whereas the plastic viscosity of a *particle* dominated concrete mix is mainly affected by the particle shape quality.

The results have demonstrated that up to 50 % of natural sand in sprayed concrete can be replaced with crushed rock materials from tunnelling, provided that the free mica content is not too high and the content of fines is kept at an acceptable level with respect to both stability and rheology of fresh concrete. Such replacement is possible even for crushed rock materials with a high content of irregularly shaped particles. This is because the effect of particle shape quality on fresh concrete properties is somewhat reduced for sprayed concrete, as this type of concrete typically is proportioned with a high matrix volume. However, the effect of particle shape quality increases with increasing content of irregularly shaped particles. Hence, replacing all natural sand with crushed rock materials from tunnelling will be unreasonable technically, economically and environmentally, unless dedicated efforts are made to improve the particle shape quality.

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TABLE OF CONTENT

GLOSSARY OF ABBREVIATIONS AND TERMS

Basic mix	-	Fresh sprayed concrete before entering the host (before adding accelerators)
BET analysis		Brunauer-Emmett-Teller analysis
Binder	-	Cement + cementitious additives (silica fume, fly ash, slag)
Cement paste	-	Cement + water + admixtures
Classification of fines	-	Removal of fines in the crushing process, which includes typically wet classification (washing) and sometimes dry classification.
Coarse aggregates		Aggregates with $D \geq 4$ mm and $d \geq 2$ mm according to NS-EN 12620, or aggregates with $d \geq 8$ mm according to Norwegian practice
Cohesion	-	The tendency of similar particles to stick together.
Compactability	-	Ability of fresh concrete to fill out the formwork and let off encapsulated air pockets during reworking
Continuous grading	-	Grading where the particles are distributed over all fractions
Crushed aggregates	-	Crushed rock materials used as concrete aggregates
Crusher fines	-	Fines generated during the crushing process
D&B	-	Drilling and Blasting
Designed concrete	-	Concrete for which desired properties and additional characteristics if any are specified to the producer, who is responsible for providing a concrete conforming to these specifications
DoP	-	Declaration of performance
Equidimensional particles	-	Rounded and/or cubical particles
f/b ratio	-	Fines/binder ratio
Filler	-	Aggregates containing predominantly particles ≤ 0.063 mm, which are used in concrete to achieve certain advantageous properties
Fine aggregates	-	Aggregates with $D \leq 4$ mm according to NS-EN 12620
Fines	-	All aggregate particles ≤ 0.063 mm according to NS-EN standards or all aggregate particles ≤ 0.125 mm according to the PM model
LOI	-	Loss of Ignition
Mobility	-	Ability of fresh concrete to move due to forces acting on it
Natural graded 0 – 8 mm aggregates		Natural aggregates or combined natural/crushed aggregates with $D \leq 8$ mm according to NS-EN 12620
NB7	-	Norwegian Concrete Association's publication 7 "Sprayed Concrete for Rock Support"

Non-equidimensional particles	-	Flaky and elongated particles
Open grading	-	Grading where the particles are concentrated in some some few fractions
PM model	-	Particle-matrix model
Pozzolans	-	Cementitious additives, including silica fume, fly ash and slag
PSD	-	Particle size distribution
Rheology	-	The study of flow of matter, primarily in the liquid state
Sand aggregates	-	Aggregate with grading 0 – 8 mm according to Norwegian practice
Saturated surface dry state	-	The condition when the aggregate particles are saturated, but without free or excess moisture on the surface
SCC	-	Self compacting concrete
sf	-	Silica fume
Singular fractions	-	The particle size fractions that are normally used in the presentation of grading curves, i.e. 0.063 mm – 0.125 mm, 0.125 mm – 0.25 mm, 0.25 mm – 0.5 mm, 0.5 mm – 1 mm etc.
SP	-	Superplasticizer
Specific surface area	-	Ratio of the total surface area of the aggregate to the mass or volume of the aggregate
Stability	-	Ability of fresh concrete to retain its homogeneity both at rest and subject to loads, e.g. During transport, casting and compaction
TBM	-	Tunnel boring machine
TBM muck	-	Excavated rock materials from TBM
VSI	-	Vertical shaft impactor
w/c ratio	-	The ratio of water content to cement content, also referred to as the mass ratio
Water demand	-	Water absorption + water required to wet all solids = water required to achieve a certain workability (slump)

LIST OF SYMBOLS

$\dot{\gamma}$	-	Rate of shear [s^{-1}]
τ_0	-	Yield shear stress [Pa]
D	-	Upper sieve aperture size
d	-	Lower sieve aperture size
f	-	Fines content [%]
g (G)	-	Moment of initial yield of the fresh concrete [Nm]
h (H)	-	Proportionality or rate of change [Nms]
IF	-	Impact factor
N	-	Speed of rotation [s^{-1}]
T	-	Torque [Nm]
v	-	Void content [%]
WA	-	Water absorption after immersion for minimum 24 h [wt-% of oven-dry material]
μ	-	Plastic viscosity [Pa·s]
τ	-	Shear stress [Pa]
ρ_{ssd}	-	Particle density of the saturated and surface-dried sample [Mg/m^3]
λ_Q	-	Flow resistance [-]
ρ_b	-	Loose bulk density [Mg/m^3]
ρ_p	-	Particle density [Mg/m^3]
k	-	Efficiency coefficient for pozzolans

1 INTRODUCTION

1.1 Motivation

Norway is one of many countries in the world that has had long traditions in using natural sand and gravel resources as aggregate supplies for concrete production. The enormous increase in demand for concrete production and the consequential increase in aggregate consumption has resulted in shortage of natural aggregate resources, especially in terms of suitable materials for concrete production [1] [2]. This is the case for many urban areas in Norway [2]. It is claimed that if the current exploitation rate remains, it is likely that the most valuable natural sand and gravel resources in Norway will be depleted within 10 – 30 years [1] [3]. These resources are not only important for concrete production, but also for wildlife and groundwater.

Furthermore, the current restricted availability of good natural sand and gravel resources has given rise to another undesirable trend in the concrete industry. As the natural aggregate resources become more and more limited with time, the transport distances between aggregate supplies and construction sites increase, which in turn lead to substantial costs and pollution. It is estimated that approximately 140 000 tons of CO_2 was emitted due to transportation of aggregates in 2012 [2]. In fact, Norway spends already more energy to transport than to produce aggregates [2]. There is reason to believe that this negative trend will proceed unless significant changes are enforced in the nearest future.

While the natural aggregate resources in Norway suffer a diminishing trend, great amounts of rock materials are generated from tunnelling. In the most recent times, it is estimated that around 6 million m^3 or around 15 million tons of rock materials are extracted in Norway every year [4]. Up until recently, rock materials from tunnelling have been regarded as an excess material with limited application. The major part of these materials is deposited in sea or landfills, posing an impact on the environment, both in terms of destroyed habitats for wildlife and marine life and increased CO_2 emission from transportation.

Several authors claim that the solution to these aforementioned problems is to exploit crushed aggregates, including rock materials from tunnelling, in a greater extent [1] [2] [3] [5]. In fact, crushed aggregates have already gained increased attention in the concrete industry, and recent research on a new type of crusher (Vertical Shaft Impactor) has given the industry the opportunity to step up and change the current situation [1] [3] [5]. However, there are still many challenges related to the utilization of crushed aggregates for concrete production compared to natural aggregates. These challenges sum up to a more demanding production procedure and consequently increased costs, which explains why the concrete industry still has not embraced the new methodology proposed by recent research. The industry still has a long way to go and further research must be undertaken in order to find more sustainable solutions.

1.2 Research question

This master thesis is aimed at evaluating the possibility of using processed rock materials from tunnelling as aggregates for sprayed concrete. Hence, both the possibility of using excess material and the possibility of producing concrete locally will be assessed. In order to do so, several crushed rock materials will be studied in terms of their performance in the fresh concrete and will be compared with a conventional natural aggregate. The study will involve characterization of aggregate properties and characterization of fresh concrete properties (concrete rheology). To better understand the relationship between aggregate properties and fresh concrete properties, the particle-matrix model will be applied throughout the study. The properties of the two phases comprising the fresh concrete, the matrix phase and the particle phase, will also be investigated. How all these properties are related to one another will be addressed.

1.3 Limitations

Only the basic mix, that is, the fresh sprayed concrete before it enters the nozzle, will be considered in this master thesis. Hence, neither the application of accelerators nor the hardened concrete will be addressed here and the experimental work will only be performed at the laboratory and not on-site.

The study of the influence of aggregate properties on fresh concrete properties will be limited to the geometrical properties of aggregates. These include grading, fines content, particle shape and free mica content. Hence, the study will not go into the physical- and chemical properties of aggregates.

For capacity reasons, the study of crushed rock materials' performance in fresh concrete will be limited to materials from two tunnelling projects only. Furthermore, only a few basic mixes will be investigated.

2 THEORETICAL BACKGROUND

2.1 Fresh concrete properties

2.1.1 The workability concept

The term *workability* is commonly used to describe the properties of fresh concrete. Paillere [6] defines workability as "the combination of properties of freshly mixed concrete, which enables it to be placed, compacted and finished easily without loss of homogeneity". These properties can be classified into three main properties: *stability, mobility* and *compactability* [7].

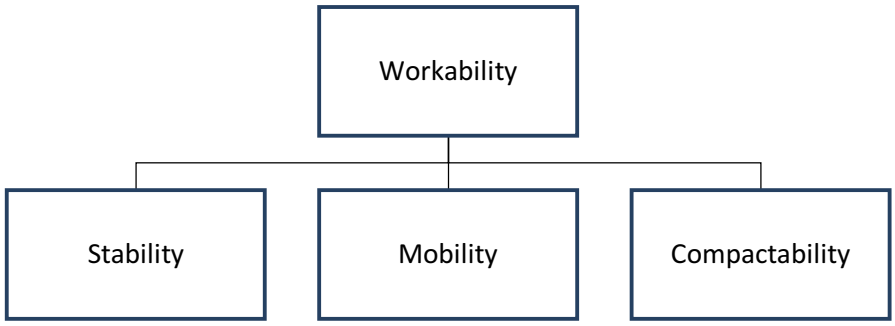


Figure 2.1: The workability concept: workability is the sum of stability, mobility and compactability.

Stability is defined as the ability of fresh concrete to retain its homogeneity both at rest and subjected to loads, e.g. during transport, casting and compaction [7]. The opposite of stability is *separation,* which is caused by internal movement of constituents due to difference in density and occurs when the gravitational forces exceed the sum of internal friction and cohesion [7]. There are three types of separation: water separation (*bleeding*), paste separation and mortar/coarse aggregate separation (*segregation*) [7]. Appropriate preventive measures depend on the type of separation. Possible measures include using aggregates with a "smooth" (dense) grading curve, using fillers or increasing the content of fines, using stabilizing admixtures or limiting the use of plasticizing admixtures [7].

Mobility[1] is defined as the ability of fresh concrete to move by means of forces acting on it [7]. This property is restricted by particle friction, cohesion and viscosity, or more precisely the flow resistance of the liquid phase in concrete (will be presented later) [7]. In general, higher mobility can be achieved by reducing the effect of one or more of the aforementioned factors. This is normally achieved by increasing the content of cement paste (reducing interparticle friction) or using plasticizing admixtures or air entraining admixtures (lowering the viscosity) [7]. The first option is the most robust one as it provides a concrete that is less sensitive to variation in the constituents' properties and less prone to separation [7], but at the same time the least beneficial one with respect to economy and risk of drying and shrinkage as a higher cement content is required.

Compaction is defined as the ability of fresh concrete to fill out the formwork and let off encapsulated air pockets during reworking [7]. While the stability and mobility of sprayed concrete are strongly influenced by the mix design, the compactability of sprayed concrete is mainly governed by the spraying procedure. Compaction of sprayed concrete takes place on the substrate and is primarily ensured by adequate shooting force during spraying [8].

[1] The term *mobility* is comparable with the term *flowability*. Throughout this study, the two terms will be used interchangeably.

The term workability is not unambiguous in the sense that the definition of good workability, or bad workability for that matter, varies from concrete type to concrete type, depending on several factors, e.g. type of structure, transport, casting- and compaction technique [7]. In practice, good workability ranges from low-flowable mixtures for paving concretes, requiring high compaction energy, to high-flowable mixtures for self-compacting concretes (SCC), requiring no compaction energy [7]. For sprayed concrete, a stable mixture that flows easily and smoothly is desirable. In fact, the term *pumpability* is commonly used to describe the desired properties of sprayed concrete. Paillere [6] defines pumpability as "the ability to convey the fresh concrete by pressure through either a rigid pipe or a flexible conduit" and consider pumpability as one of the properties that constitute workability. Other authors [9] [10] define pumpability as the combination of mobility and stability. In this study, it is expected that a pumpable concrete is achieved with a workable concrete. Hence, only the workability concept will be further discussed.

2.1.2 Rheology of fresh concrete

It is common to consider fresh concrete as a non-Newtonian fluid[2] when describing the mobility of fresh concrete [7].

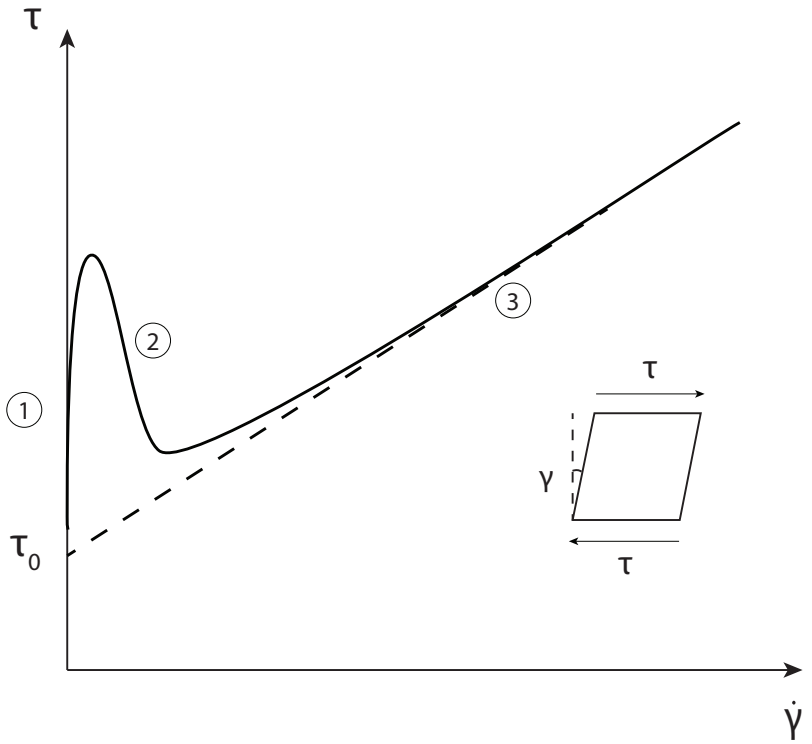


Figure 2.2: The rheological behaviour of fresh concrete. Figure after [7] (modified) .

The behaviour of fluids in terms of motion is commonly described by means of the relationship between the resistance against deformation represented by the fluid and the rate of deformation to which the fluid is subjected. Figure 2.2 shows the typical rheological behaviour of fresh concrete. The *shear stress*, τ, is the deformation resistance, whereas the *rate of shear*, $\dot{\gamma}$, is the deformation rate.

[2] A non-Newtonian fluid is a fluid that does not follow Newton's law of viscosity: $\tau = \mu \cdot \dot{\gamma}$

In general, the rheological behaviour of fresh concrete when subjected to increasing loading can be divided into three stages [7]:

- Stage 1:
  Elastic behaviour, characterized by an approximately linear relationship between the shear stress and the rate of shear. The elastic capacity is attributed to interparticle bonds.
- Stage 2:
  Plastic behaviour, characterized by a drop in shear stress due to formation of sliding planes and particle bond breakage [11].
- Stage 3:
  Viscous behaviour, again characterized by an approximately linear relationship between the shear stress and the rate of shear. The resistance against deformation is now dominated by the flow resistance and to a lesser extent by the interparticle bonds.

When fresh concrete is subjected to decreasing loading, on the other hand, it will have a viscous behaviour all the way until it is at complete rest [7]. The difference in the rheological behaviour at loading and unloading is called *hysteresis*. The lowest shear stress needed to keep the fresh concrete in motion, which is determined by unloading the concrete, is called the *dynamic yield shear stress*[3] or the *yield shear stress* or simply the *yield stress,* τ_0.

The rheological behaviour of fresh concrete, as described above, is difficult to describe without involving many parameters. Hence, using the *Bingham model* as a simplification was proposed by Tattersall and Banfill in 1983 [12]. The following relationship holds for Bingham fluids:

$$\tau = \tau_0 + \mu \cdot \dot{\gamma}$$

where

τ - shear stress [Pa]
τ_0 - yield shear stress [Pa]
μ - plastic viscosity [Pa·s]
$\dot{\gamma}$ - rate of shear [s^{-1}]

The relationship implies that the fluid has a certain elastic shear capacity, that is, the material must be loaded up to the yield shear stress, τ_0, before it starts to flow. After this point, the shear stress, τ, increases linearly with the rate of shear, $\dot{\gamma}$. The constant of proportionality is called the *plastic viscosity*, μ.

Hence, by considering fresh concrete as a Bingham fluid, only two parameters τ_0 and μ need to be determined to describe the rheological behaviour of fresh concrete. However, these parameters are difficult to determine in practice and thus existing test methods use analogous, measurable quantities instead. The *two-point workability test* [12] gives the parameters *g* and *h* by measuring the relationship between the rotational speed of a rotor placed inside a cylindrical container filled with fresh concrete and the resulting torque exerted on the concrete [7]:

[3] The *static yield shear stress* is determined by loading the concrete and defines the concrete's elastic capacity (the peak in Figure 2.2).

$$T = g + h \cdot N$$

where

T - torque [Nm]
g - moment of initial yield of the fresh concrete [Nm]
h - proportionality or rate of change [Nms]
N - speed of rotation [s^{-1}]

The parameters g and h are equivalent to the yield stress, τ_0, and the plastic viscosity, μ, respectively. The procedure for determining g and h by the aid of a handheld rheometer is described in section 3.3.4.6. Figure 2.3 shows the Bingham model and the relationship between torque and rotational speed used in the two-point workability test.

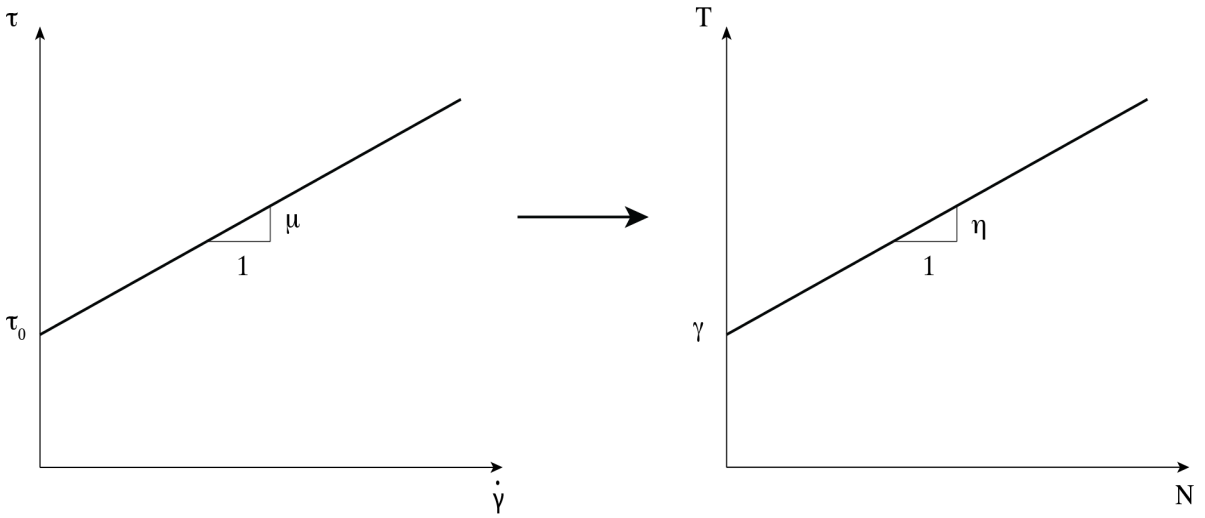


Figure 2.3: The Bingham model (left) and the relationship between torque, T, and rotational speed, N, used in the two-point workability test (right). Figure after [7] (modified).

2.1.3 The particle-matrix model

The relationship between workability and mix design of concrete can be easily described by applying *the particle-matrix model* (PM model) [13] [14]. This simplified material model, which was first introduced by Ernst Mørtsell in his doctoral thesis in 1996 [13] is applicable to the most commonly used concretes, including high-performance concrete (HPC) [15] and lightweight-aggregate concrete (LWAC) [16].

In the PM model, fresh concrete is considered as a two-phase system, consisting of a fluid material, the *matrix phase*, and a friction material, the *particle phase*. Thus, the classification of the different constituents is based on their properties and not on their origin. The matrix phase is composed of free water, admixtures and all solid materials with particle sizes ≤ 0.125 mm, i.e. cement, pozzolans and all aggregate particles ≤ 0.125 mm, also referred to as *fines*. The particle phase, on the other hand, is composed of the remaining aggregate particles, i.e. all aggregate particles > 0.125 mm.

In the PM model, the workability of fresh concrete is a function of the properties of the two phases and the volume ratio between them. This is illustrated in Figure 2.4.

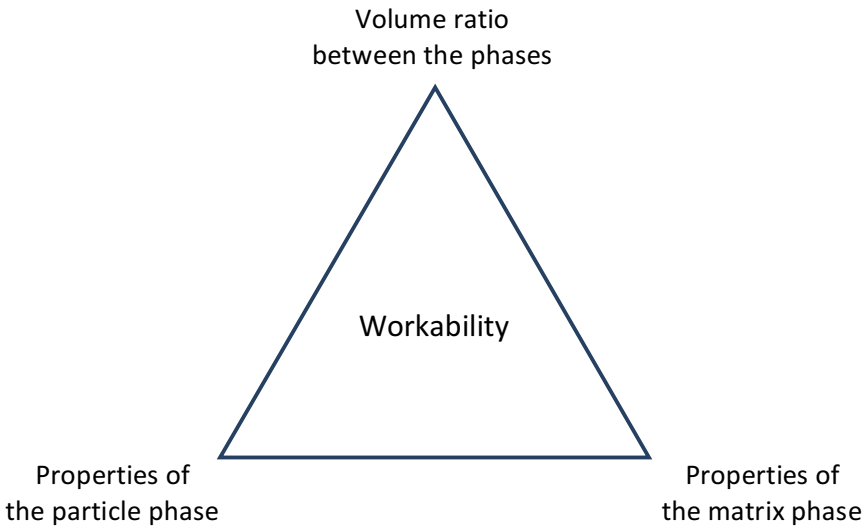


Figure 2.4: PM model – The factors influencing the workability properties of fresh concrete.

2.1.3.1 The properties of the matrix phase

The matrix phase is the flowable part of the concrete and can be considered as a tough viscous fluid [7]. Hence, the properties of the matrix phase can be described by means of its fluid properties. The *FlowCyl test* [13] [14] [15] [17] is a simple flow viscometer, which has been developed to characterize the fluid properties of the matrix phase by means of the parameter *flow resistance.* The flow resistance has certain similarities to the viscosity of a Newtonian fluid [7] [16], which is comparable to the plastic viscosity of a Bingham fluid. In fact, it has been demonstrated that there is a strong correlation between the matrix phase's flow resistance and plastic viscosity [1]. A more detailed description of the FlowCyl test is provided in section 3.3.2.

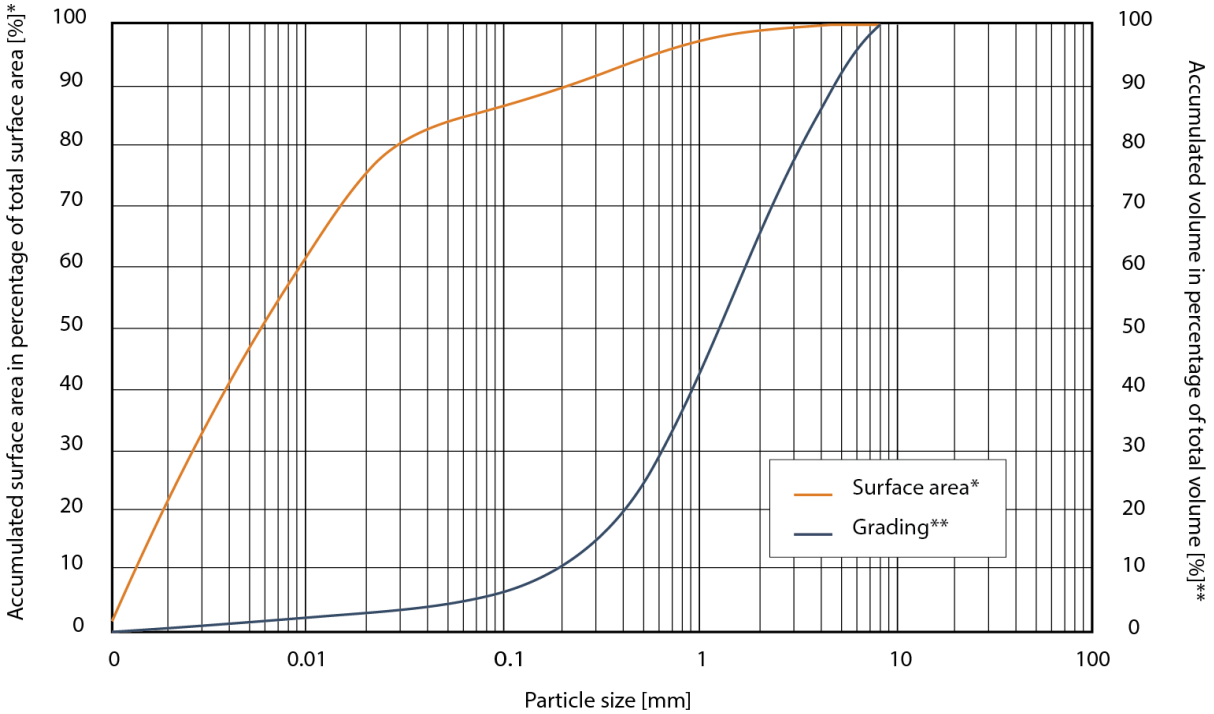


Figure 2.5: Surface area and volume represented by the different particle sizes for a specific aggregate. Figure after [18] (modified).

The reason why aggregate particles ≤ 0.125 mm, i.e. fines, are included in the matrix phase is because of their great contribution to the total surface area. Figure 2.5 shows the accumulated surface area in percentage of the total surface area for the different particles sizes for a specific aggregate, in comparison with the corresponding grading. The figure shows that the fines represent more than 90 % of the total surface area of the aggregate. In fact, it has been proven that the contribution from particles ≤ approximately 20 μm is especially significant [1] [18]. Hence, as for the other components in the matrix phase, the properties of the fines are predominantly governed by mineralogy and surface characteristics [7].

The flow resistance of the matrix phase describes the flowability of the material. A high value is related to a stiff and viscous material, whereas a low value is related to a highly fluid material. The flow resistance is increased by increasing the total surface area, i.e. by increasing the proportion of fine particles or by applying particles with higher fineness [18]. On the other hand, the flow resistance is reduced by increasing the w/c ratio and by increasing the dosage of plasticizers or superplasticizers [18].

2.1.3.2 The properties of the particle phase

The properties of the particle phase are described by means of the *void content*, also referred to as the *air voids ratio*, which is the volume of the air-filled spaces between the particles [7]. The procedure for determining the void content is described in section 3.3.1. The void content is predominantly governed by particle size distribution and particle shape [7]. These properties will be presented in section 2.2.2.

The void content is equivalent to the largest volume of the matrix phase that gives a fresh concrete with non-measurable workability, i.e. no slump [14] [16]. However, Mørtsell discovered in his doctoral thesis [13] that there is a far more complex relationship between the void content of the particle phase and the matrix volume needed at the state right before a measurable slump is obtained. As a result, he introduced the *air voids modulus*, which is a modification of the void content. The air voids modulus takes into account, among others, the fact that the effect of the properties of the finer particles on workability is more prominent [14] [16]. Describing the particle phase properties by means of the air voids modulus would have been far too comprehensive for this study, as this would have required empirical determination of a numerous parameters. Hence, a simplified PM model, using the void content instead of the air voids modulus to describe the properties of the particle phase will be applied here.

Based on the void content, the matrix volume needed to initiate movement in the fresh concrete can be estimated. To make a concrete with no slump, the matrix surplus, i.e. the matrix volume additional to the matrix volume equivalent to the void content, must typically be 20 – 40 l/m^3 [7]. To obtain higher slump values, the matrix surplus must necessarily increase to allow greater distances between particles and movements with less particle interactions. Concrete with crushed aggregates will probably require a higher matrix surplus, as the particles tend to be flaky and elongated[4] and consequently need more space to move relatively to each other. This will be addressed in section 2.2.2.4.

[4] Flaky particles are particles in which the thickness is small relative to the length and the width, whereas elongated particles are particles in which the length is considerable larger than the thickness and the width. A quantitative definition is given in section 3.2.4.

2.1.3.3 Matrix/Particle volume ratio

In the PM model, the fresh concrete is either *particle dominated* or *matrix dominated* depending on the volume ratio between the two phases [7]. These two types of particle-matrix systems are illustrated in Figure 2.6.

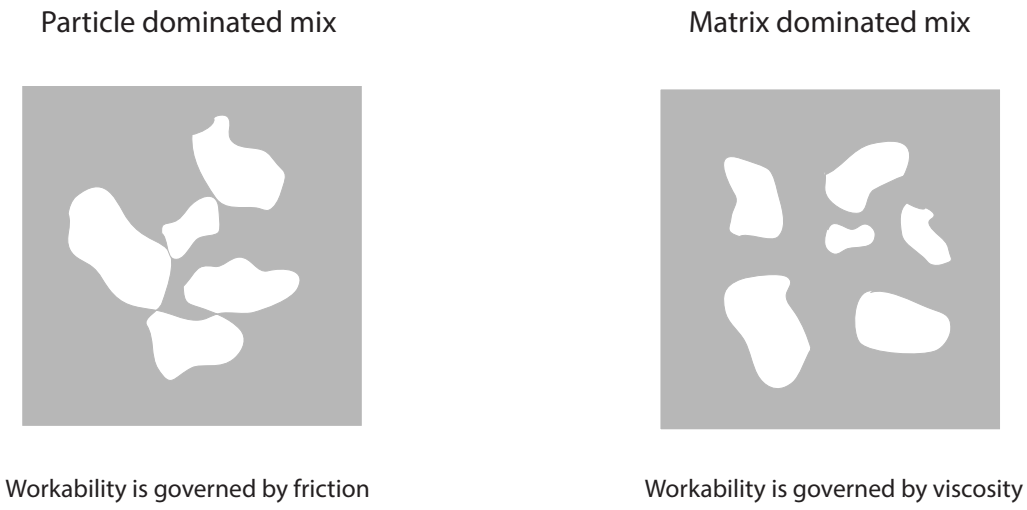


Figure 2.6: Particle dominance and matrix dominance. Figure after [7] (modified).

The workability properties of a particle dominated mix are mainly governed by particle interactions, that is, the properties of the aggregate particles in the particle phase are decisive. On the other hand, the workability properties of a matrix dominated mix are primarily influenced by the properties of the matrix phase, as the contact between the aggregate particles in the particle phase is reduced to a negligible level due to the increased matrix volume.

2.1.4 The workability function

According to the PM model, the workability, characterized by the slump, the slump-flow or other workability parameters, is a unique function of the matrix/particle volume ratio when the properties of the matrix- and particle phase are given [7] [14] [16]. The workability functions of two concrete mixes with different properties of the two phases are illustrated in Figure 2.7. The workability is presented as the slump, whereas the matrix/particle volume ratio is presented as the matrix volume.

In general, the slump increases with increasing matrix volume. This is because the matrix phase represents the flowable part of the concrete. However, increase in slump is only possible when the matrix volume exceeds the void content, i.e. when the matrix fills all the voids. Hence, the void content of the particle phase determines the starting point of the curve. The flow resistance of the matrix phase, on the other hand, determines the inclination of the curve. The higher the flow resistance, the higher the matrix volume needed to increase the slump and the flatter the curve.

At low slump values, the concrete is typically particle dominated. The slump increases slowly with the matrix volume as movements are limited by particle interactions and friction forces. At higher slump values, the concrete is in the transition between particle dominance and matrix dominance. The slump increases more rapidly with the matrix volume as the contact between the particles is gradually eliminated and the particles can move more freely relative to each

other. At high slump values, the concrete is typically matrix dominated. The slump will stabilize as movements are limited by the fluid properties of the matrix.

The slump at the transition between particle dominance and matrix dominance is not universally defined as it depends, among others, on the flow resistance of the matrix phase [7]. Sprayed concrete is typically a matrix dominated mix. The slump required for sprayed concrete lies in the range 200 – 240 mm [19].

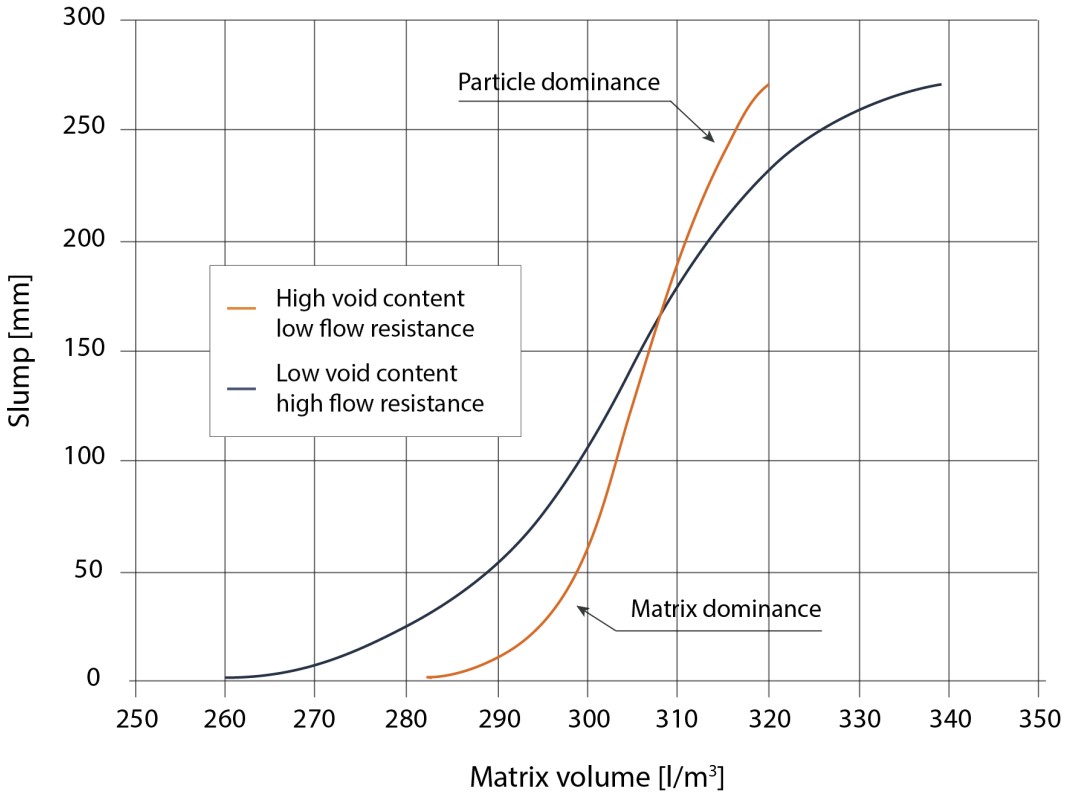


Figure 2.7: The relationship between slump and matrix volume for two different concretes. Figure after [7] (modified).

2.2 Concrete aggregates

2.2.1 Terminology

The term *concrete aggregates* is a designation for all rock materials used for concrete production. According to the Norwegian practice, *sand aggregates* are concrete aggregates in the fraction 0 – 8 mm, whereas *coarse aggregates* are concrete aggregates in the coarser fractions, for instance 8 – 16 mm or 8 – 22 mm [7]. In this study, the term *crushed aggregates* refers to all types of crushed rock materials used as concrete aggregates, whereas the term *natural aggregates* refers to concrete aggregates extracted from natural resources (deposits). Further in this study, crushed aggregates in the sand- and coarse fraction will be denoted as *crushed sand* and *crushed stone*, respectively.

Note that NS-EN 12620 [20] distinguishes between *fine aggregates* ($D \leq 4$ mm), *natural graded aggregates* ($D \leq 8$ mm) and *coarse aggregates* ($D \geq 4$ mm and $d \geq 2$ mm). In practice, fines aggregates are in the fraction 0 – 2 mm or 0 – 4 mm, natural graded aggregates in the fraction 0 – 8 mm and coarse aggregates in the fraction 4 – 8 mm, 8 – 16 mm or 16 – 22 mm [18]. These terms will be used when referring to the standard.

2.2.2 Aggregate properties influencing fresh concrete properties

As aggregates normally occupy 65 – 75 % of the concrete volume, their properties have necessarily a significant impact on the properties of the concrete in both the fresh- and the hardened state [7]. An "influence chart" showing the aggregate properties that influence the flow resistance of the matrix phase and the void content of the particle phase is shown in Figure 2.8.

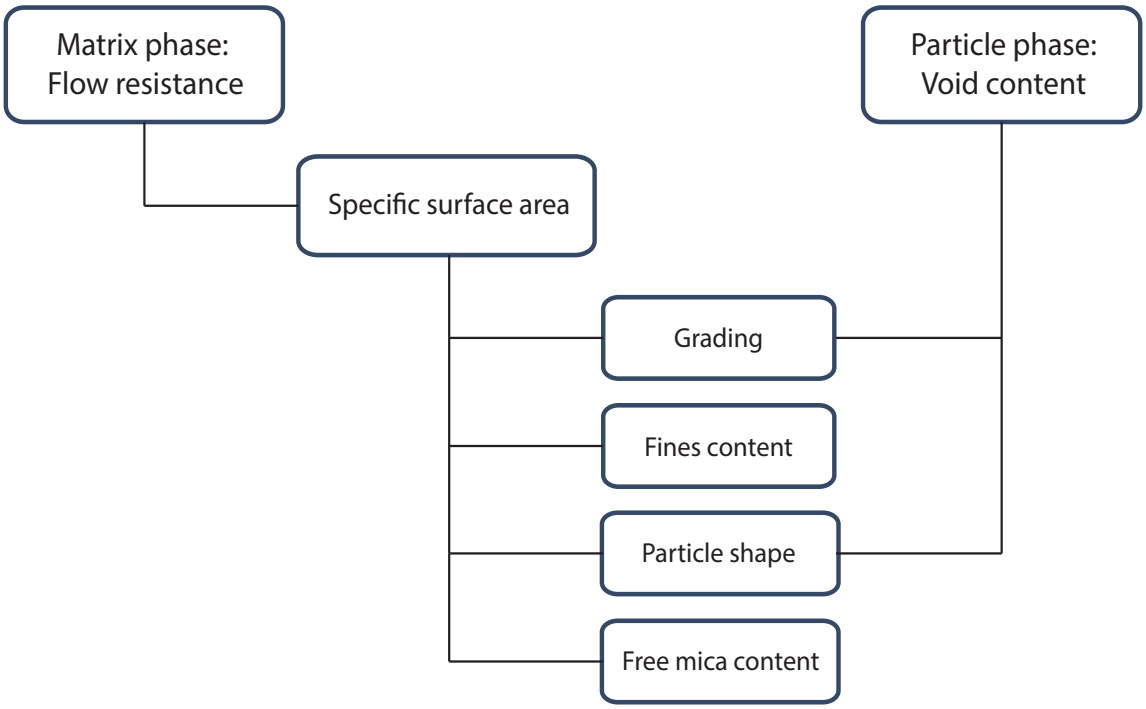


Figure 2.8: The geometrical properties of aggregates influencing the properties of the particle phase and the properties of the matrix phase.

2.2.2.1 Specific surface area

The surface area of aggregates is often expressed as the *specific surface area* of aggregates, which is the ratio of the surface area to the weight (or volume) of the aggregate particles. The specific surface area of aggregates determines the amount of water necessary to wet all the aggregate particles [21]. Hence, this parameter is strongly related to the water demand of concrete and has a great impact on the fresh concrete properties. The higher the water demand, the higher the cement content needed to keep the w/c ratio constant and the higher the matrix volume needed to achieve a certain workability.

Furthermore, as illustrated in Figure 2.8, the specific surface area of aggregates influences primarily the flow resistance of the matrix phase. In fact, it has been proven in several studies [1] [22], that the flow resistance of the matrix phase is linearly correlated to the specific surface area of the fines of which the matrix phase is composed. Hence, the flow resistance of matrix materials can be adjusted by altering the fines' surface area, which in practice is done by altering the fines grading or the total volume of fines. Figure 2.9 shows the linear relationship between the flow resistance and the surface area of fines for two different matrix materials, in which the variation in surface area has been achieved by varying the fines content.

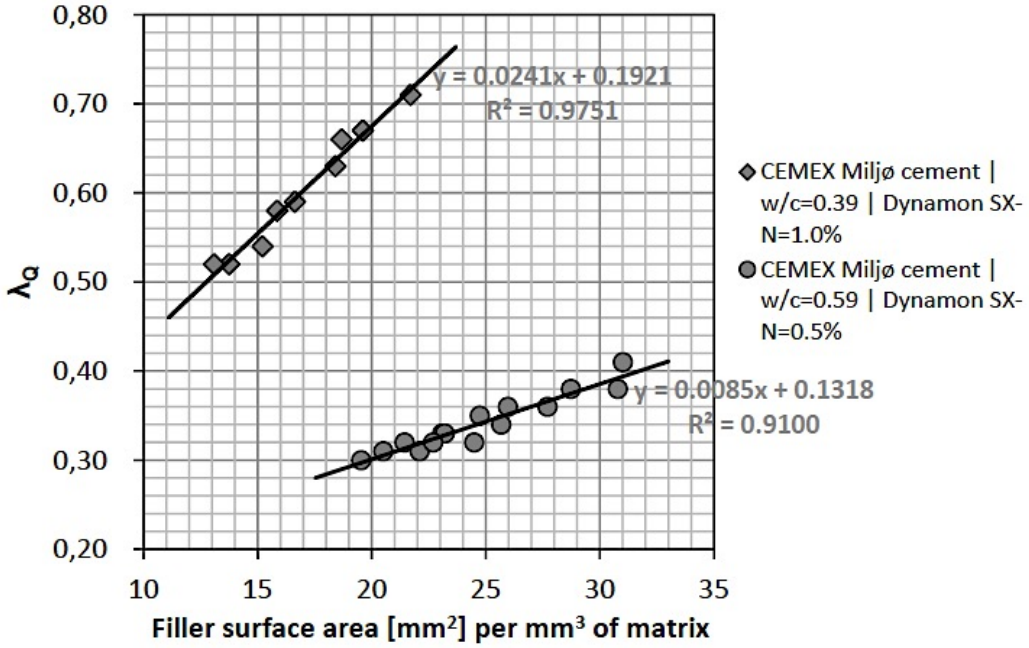


Figure 2.9: The relationship between the flow resistance and the surface area of fines (per matrix volume) for two different matrix materials. Figure after [22].

The specific surface area of aggregates is governed by the geometrical properties of aggregates; the grading, the fines content, the particle shape and the free mica content. A high specific surface area is achieved when the content of fines and free mica is high and when the proportion of irregularly shaped particles is high [21]. The specific surface area is also affected by the grading as the greatest contribution to the surface area is provided by the smallest particles, especially particles ≤ approximately 20 μm, as already mentioned in section 2.1.3.1.

2.2.2.2 Grading

The grading of aggregates, especially the sand fraction, has a significant impact on the workability of concrete in terms of mobility and stability [7] [21]. This parameter governs the amount of voids that must be filled with matrix as well as the aggregate surface area that must be coated with matrix [21]. In general, the grading curve should be carefully adjusted for the specific aggregate and the specific concrete composition to ensure that the optimal workability is achieved in an economical manner.

A *dense grading* of aggregates is in most cases beneficial for the workability of fresh concrete [7] [18] [21]. This is achieved when all the singular fractions (0.063 – 0.125 mm, 0.25 – 0.5 mm, 0.5 – 1 mm etc.) are present and evenly distributed, allowing the particles to be densely packed and thus limiting the necessary matrix volume to fill the voids and to achieve relative motions between the particles. The relationship between particle size distribution and particle packing density is shown in Figure 2.10. The opposite of a dense grading is an *open grading* and occurs when the particles are concentrated in one or some few fractions. The terms dense grading and open grading refer to the degree of packing [18].

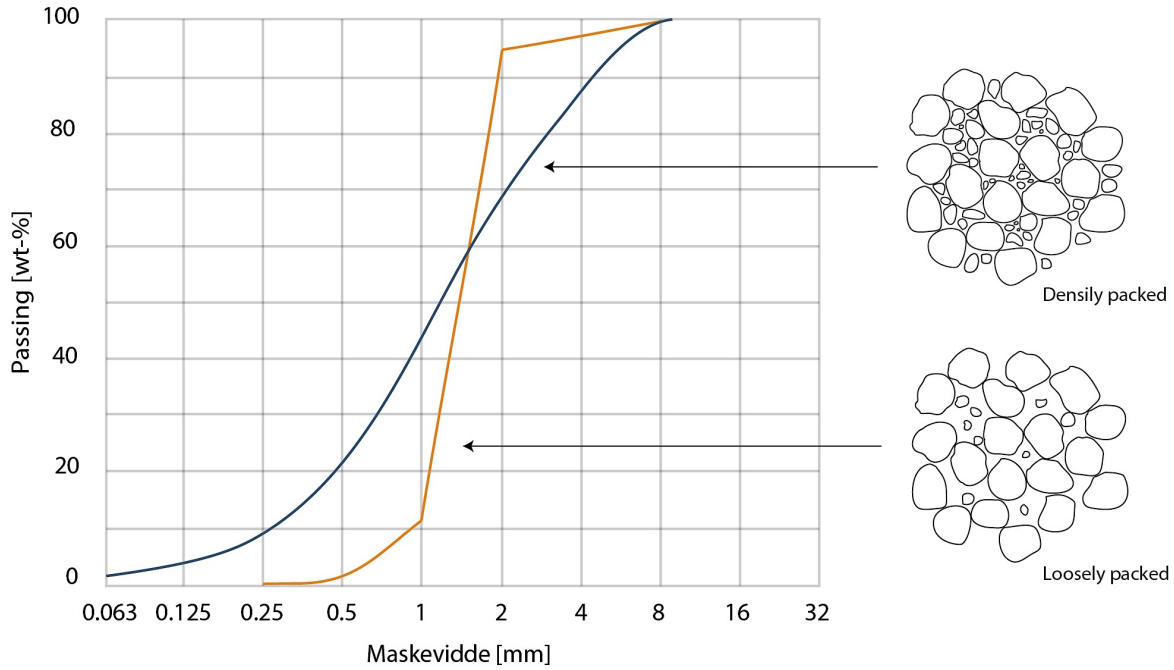


Figure 2.10: The blue curve represents a dense grading curve, whereas the orange curve represents an open grading curve.

For concrete requiring a high slump value and especially concrete that needs to be pumped, a "smooth" or dense grading is preferable to avoid segregation [7] [21]. NB7 [23] recommends that none of the singular fractions (0.063 – 0.125 mm, 0.25 – 0.5 mm, 0.5 – 1 mm etc.) exceed 30 % of the total aggregate mass.

2.2.2.3 Fines content

The influence of fines on the fresh concrete properties depends on the nature of the fines [21]. In this section, fines refer to the fine fraction of the aggregates, specifically particles ≤ 0.063 mm, without any contamination such as deleterious clays.

In general, the fines content of aggregates plays an important role for the workability of fresh concrete in terms of mobility (viscosity) and stability (segregation and bleeding) [7] [21].

According to the PM model, an increase in the fines content will contribute to increase the matrix volume, and thus to increase the mobility of the fresh concrete. However, an exaggerated increase in the fines content, especially the content of particles ≤ approximately 20 µm, will increase the flow resistance of the matrix phase significantly, resulting in a highly viscous concrete with reduced mobility [18]. This is illustrated in Figure 2.11 where the workability, characterized by the slump, is presented as a function of the fines content per m^3 concrete for three different aggregates. The figure also shows the grading curves of the aggregates. Note that the most apparent decrease in slump is observed for the material "Tau", which has the finest grading and thus the highest content of particles ≤ 20 µm. The reason why particles ≤ approximately 20 µm play such an important role is their major contribution to the surface area, as shown in Figure 2.5 in section 2.1.3.1.

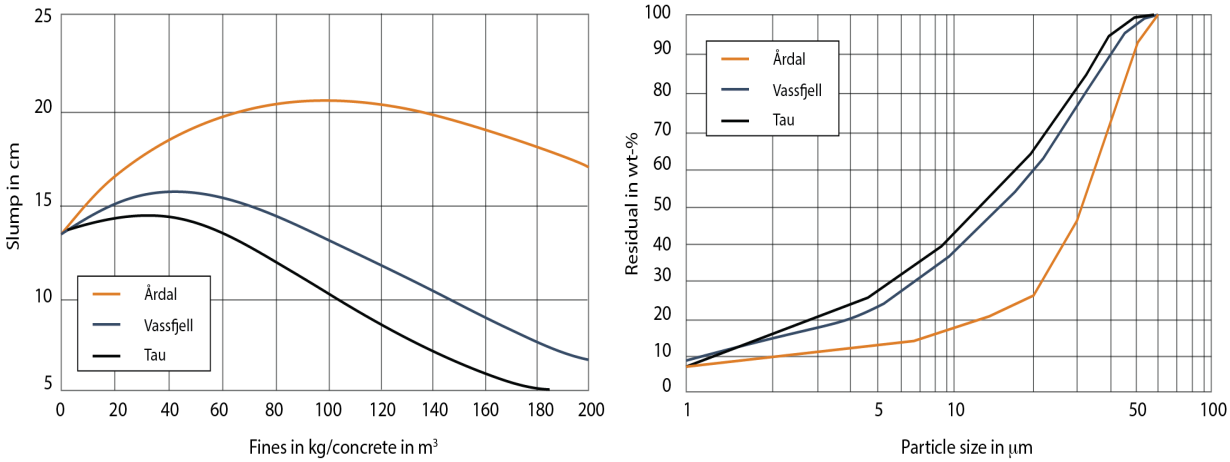


Figure 2.11: The relationship between the slump and the fines content for three different aggregates (left) and the grading curves of the aggregates (right). Figure after [18] (modified).

In contrary to the mobility of fresh concrete, a certain fines content is generally beneficial for the stability and the pumpability of fresh concrete. The fines help to control segregation and bleeding (see section 2.1.1) by making the fresh concrete more cohesive [7] [21]. The cohesiveness is attributed to the increased surface area of the aggregate. In concrete proportioning, the fines content is therefore always a compromise between the requirement of concrete mobility and the requirement of concrete stability.

2.2.2.4 Particle shape

The particle shape is another important parameter that influences the fresh concrete properties [7] [18] [21]. It is common knowledge that irregularly shaped particles are less favourable for the workability of concrete than regularly shaped particles as a higher matrix volume is required to obtain a certain flowability. Hence, in this study, the particle shape quality of an aggregate is described as *high* when the particles are predominantly equidimensional (rounded and cubical), and correspondingly as *poor* when the particles are mostly non-equidimensional (flaky and elongated).

In general, flaky and elongated particles allow less dense packing and cause more space between the particles than rounded and cubical particles. In addition, irregular geometries induce high interparticle friction, resulting in limited relative motions between the particles and a less mobile concrete mix. Figure 2.12 shows that the required matrix/particle volume ratio to obtain free movement of particles increases with decreasing shape quality. In addition to the necessary matrix volume to fill the space between the particles, additional matrix volume

is required to lubricate the particles and enable relative movements to obtain a desired workability (slump). In the case of aggregates with poor particle shape quality, the required matrix volume for both filling the voids and lubrication is higher compared to aggregates with high particle shape quality.

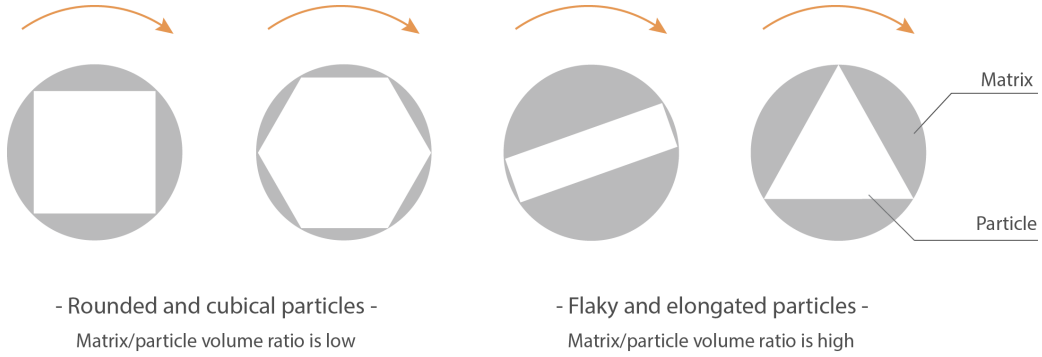


Figure 2.12: The necessary matrix volume for rotation of particles with different shapes. Figure after [24] (modified).

A high content of non-equidimensional particles may also have a negative impact on the concrete stability as bleed water can be more easily trapped underneath the particles [21]. Furthermore, flaky and elongated particles tend to have a higher surface area than rounded and cubical particles, which contributes to increase the water demand of concrete and the flow resistance of the matrix phase [7].

It has been proven by several authors that the shape of the finest particles has the largest impact on the workability. Figure 2.13, which is extracted from Cepuritis' doctoral thesis [1], shows this relationship. In this figure, Cepuritis describes the influence of the different fraction's particle shape with the parameter *impact factor* (*IF*). The figure shows that the largest value and thus the greatest impact is posed by the particles ≤ 0.125 mm, i.e. the fines in the PM model.

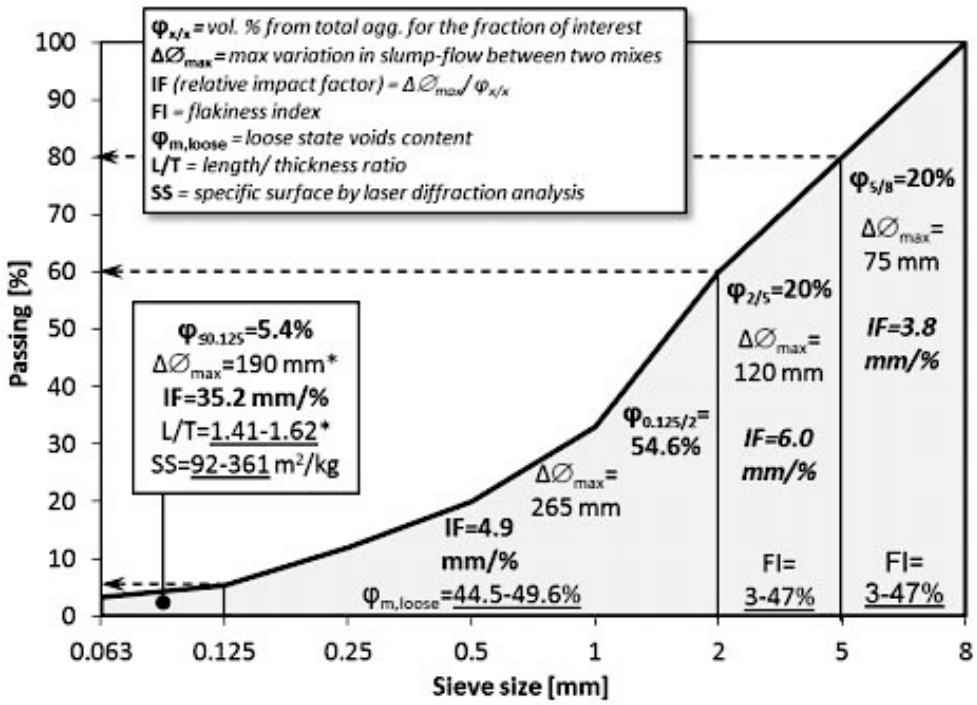


Figure 2.13: The impact of the different fraction's particle shape on the workability. Figure after [1].

2.2.2.5 Free mica content

Mica minerals are flaky minerals that may be present in the sand fraction. These minerals contribute to increase the surface area of the aggregate and consequently the water demand of the concrete [7] [18] [21]. Hence, the presence of free mica minerals in the aggregate will likely affect the fresh concrete properties negatively as a higher matrix volume is needed to achieve a certain flowability [18]. Figure 2.14 shows an example of the relationship between the workability of fresh concrete, characterized by the slump, and the mica content.

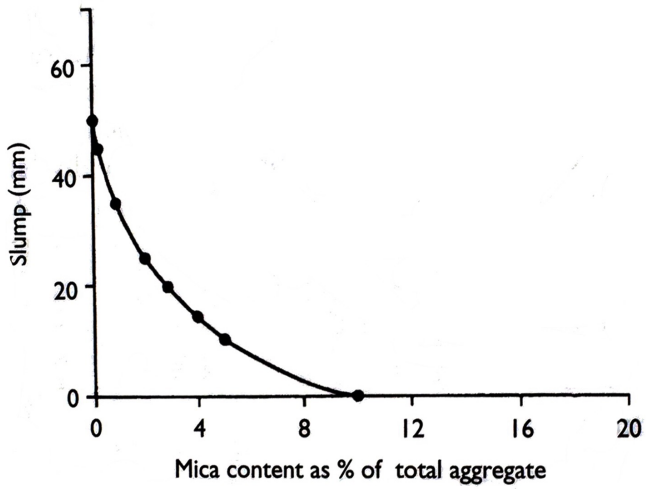


Figure 2.14: The relation between the slump and the free mica content (example). Figure after [25] .

2.2.3 Crushed aggregates

2.2.3.1 Production and processing

In Norway, crushed rock materials in the coarse fraction are already widely used for construction purposes, both as road construction materials and as concrete aggregates [18]. Use of crushed sand for concrete production is less common, but has become more common in the recent years. The limited access to high quality natural aggregates in the future has raised concerns among many aggregate producers. Combining natural- and crushed sand is becoming a more and more common practice [18].

Selection of suitable rock types plays a fundamental role in the production of crushed aggregates as the mineralogical composition form the basis for the final properties of the aggregates [7]. The major part of the Norwegian bedrock is suited as concrete aggregates. Gneiss, granite and sedimentary- and volcanic rocks in the area around Oslo are rock types of especially good quality [7] [18]. Note that some gneiss and granite contain mica, which is disadvantageous for the workability of concrete and should therefore be taken care of in the production, e.g. by washing (disputed) or by froth floatation.

The production of crushed sand is normally combined with the production of crushed stone, as the crushing process always generate some additional fine particles, which is commonly referred to as *crusher fines* [1]. In the production of crushed stone, the crushing process is typically divided into three particle-size-reduction stages; *primary stage, secondary stage* and *tertiary stage* [1]. A *quaternary stage* is included when the aim is to produce crushed sand with high quality (improved PSD and particle shape) [1]. A schematic illustration of the typical set-up of a crushed sand production plant is presented in Figure 2.15.

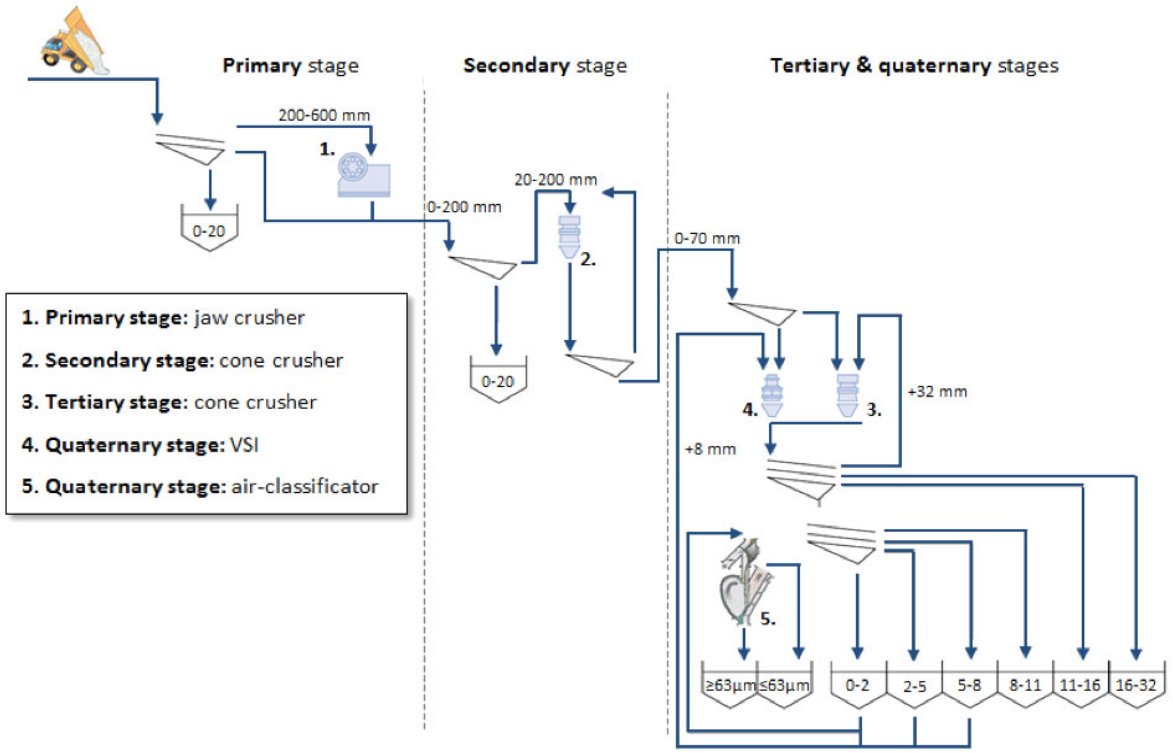


Figure 2.15: The typical set-up of a crushed sand production plant. Figure after [1].

Primary stage: The primary stage is aimed at crushing blasted rock- or excavated rock fragments of significant sizes into particles < 200 mm [1]. The crushing in this stage is normally accomplished with a *jaw crusher* or a *gyratory crusher*, which are compression crushers [1].

Secondary stage: The secondary stage is aimed at crushing the particles from the previous stage into particles < 70 mm [1]. The crushing in this stage is normally accomplished with a *cone crusher*, which is another type of compression crusher [1] [3].

Tertiary stage: The tertiary stage is aimed at crushing the particles from the previous stage into particles < 32 mm. The crushing in this stage is normally accomplished with a modern high-speed cone crusher [1]. In addition to size reduction, the particle shape of the coarser particles (particles > 8 mm) is also improved in this stage [1]

Quaternary stage: The quaternary stage is aimed at improving the particle shape of the finer particles (particles ≤ 8 mm). The shape alteration is normally accomplished with a cubisator or a so-called VSI (Vertical Shaft Impact) crusher. The crushing technique implemented in this type of crusher imitates the crushing process that can be found in the nature [18]. Hence, it is possible to produce crushed sand with a similar particle shape quality as natural sand with the VSI crushers, provided that the crushing process is optimized for the specific rock types [26]. Typical differences in particle shape between crushed- and natueral aggregates will be addressed in section 2.2.3.2. It has been proven that crushed sand from a VSI crusher has both better particle shape and lower void content than crushed sand from a cone crusher [26].

However, there are some disadvantages associated to the VSI crushers. The main disadvantage is that these crushers generally produce higher amount of fines compared to other crushers [3] [26]. Experiences imply that they can increase the content of particles < 4 mm with more than 30 % and particles < 0.125 mm with 50 % [3]. Hence, the crushing step is often followed by a wet- and/or air (dry) classification step in order to remove some of the fines [1] [3].

2.2.3.2 Crushed aggregates vs. natural aggregates

Figure 2.16 (left) shows the characteristic particle size distributions of natural- and crushed sand. Natural aggregates typically have an *open* grading where the particles are loosely packed. The particles tend to concentrate within a narrow particle size range, typically in the range 0.5 mm – 2 mm [18]. Crushed aggregates, on the other hand, typically have a *dense* grading where the particles are densely packed. Furthermore, crushed aggregates typically contain a higher amount of fines (particles ≤ 0.125 mm), which is related to how crushed aggregates are produced. As mentioned in section 2.2.3.1, even in the production of coarse aggregates, a high amount of so-called crusher fines is generated during the crushing process.

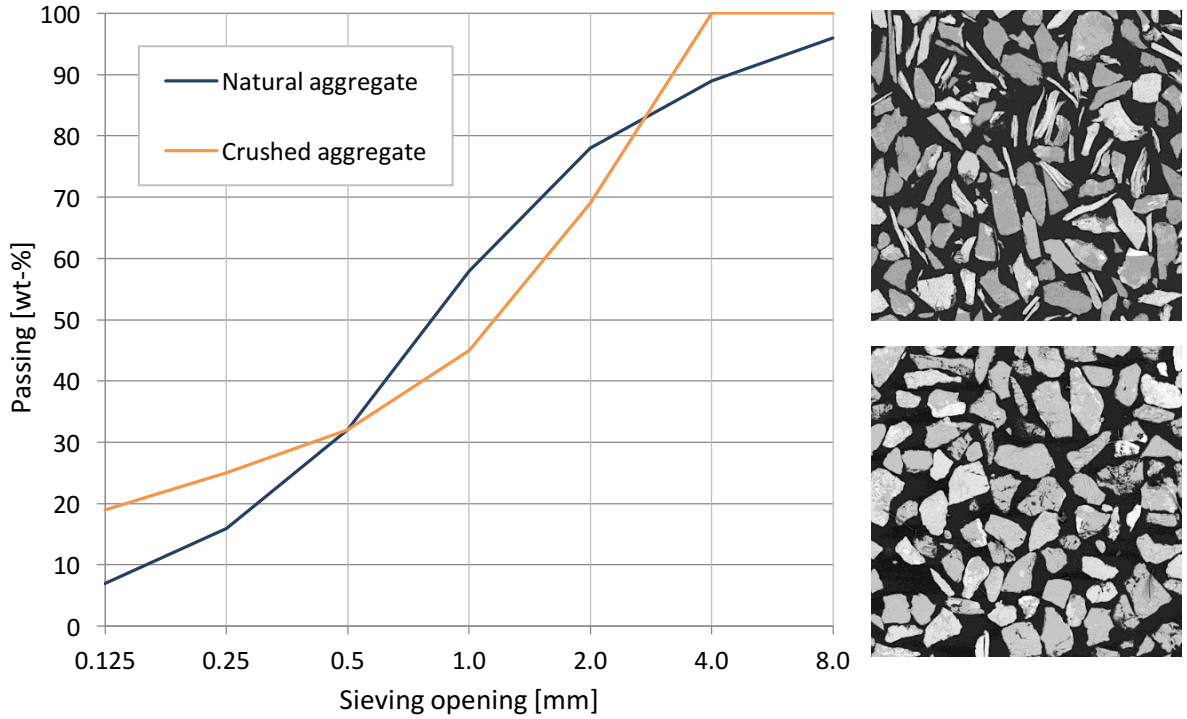


Figure 2.16: The typical grading curves of crushed- and natural aggregates (left). Figure after [18] (modified). The typical particle shape of crushed aggregates (right top) and natural aggregates (right bottom). The particles are in the fraction 0.125 – 0.250 mm. Figures after [5].

In general, crushed aggregates have a poorer particle shape quality than natural aggregates in the sense that their particles tend to be more flaky and elongated. The higher particle shape quality of natural aggregates is attributed to the natural wear from ice and water during transport which the aggregate particles have been subjected to over long time. The typical differences in particle shape between crushed- and natural aggregates are shown Figure 2.16 (right).

As addressed in section 2.2.2.2, a dense grading is more beneficial for the workability properties of concrete in the sense that a lower matrix volume is needed to fill the space between the particles. However, this is not always the case for crushed aggregates with high proportion of non-equidimensional particles, as the interparticle friction, which typically is higher for flaky and elongated particles, may become unfavourable high with high particle packing density [21]. Hence, one should be careful stating that crushed aggregates have a more workability-beneficial grading than natural aggregates. The effect of high content of irregularly shaped particles combined with high particle packing density will not be further discussed here, as this needs to be evaluated for each case.

What is certain is that crushed aggregates without further processing (wet/dry classification and VSI) usually have an excessive amount of fines and a high content of irregularly shaped particles. Hence, crushed aggregates normally require a higher matrix volume to obtain a certain flowability due to the higher amount of voids, the higher friction forces between particles, as well as the higher water demand. The flow resistance of the matrix phase is also higher due to the higher specific surface area.

With increased demand for cement and consequently increased material costs, crushed aggregates are normally less suitable for concrete production than natural aggregates. The utilization of crushed sand is especially challenging, as the particle shape quality of the smallest particles represents the greatest impact on the workability of concrete (see Figure 2.13 in section 2.2.2.4). In order to ensure good rheological properties and at the same time keep the material costs at an acceptable level, it is not common among Norwegian concrete producers to use concrete aggregates with a crushed sand/total sand ratio greater than 50 % [18]. However, based on recent research, it is believed that a higher utilization of crushed sand can be obtained by including VSI and wet- and dry classification in the crushing process. In fact, the aggregate supplier Velde AS has already started producing 100 % crushed aggregates for concrete production based on this technology.

2.3 Sprayed concrete

2.3.1 Definition of sprayed concrete

Sprayed concrete, also known as *shotcrete*, is mortar or concrete that is forced through a nozzle with compressive air and pneumatically projected onto a surface at high velocity [27]. This process can be carried out in two ways: the *wet spray method* and the *dry spray method*. The wet spray method is the most applied approach in Norway [18] and this study will only refer to this method.

The wet spray method involves primarily a pumping machine connected to a feed line and a nozzle. A typical set-up of the process is schematically illustrated in Figure 2.17.

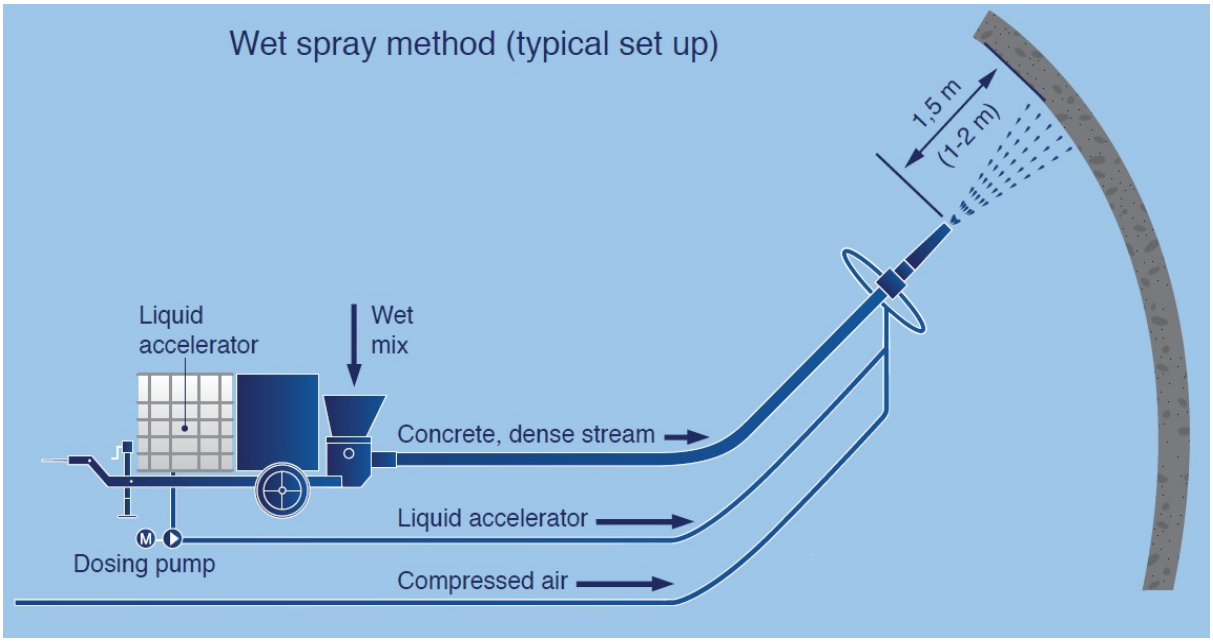


Figure 2.17: Schematic illustration of the wet mixing method. Figure after [28].

Bulk materials, i.e. aggregates, cement and cementitious additives, are mixed together with water and admixtures, except for accelerators, before being fed into the pumping machine [27]. Usually the bulk materials, the water and the admixtures are pre-mixed by the concrete producer and transported to the site with mixer trucks. If necessary, fibres are added directly into the truck. The aforementioned components constitute the fresh concrete that is usually referred to as the *basic mix* [23]. Eventually, the basic mix is transferred to the pumping machine and then pumped to the nozzle through the feed line, where appropriate dosages of compressed air and accelerators are added in to the mix to assure well-distributed projection, compaction and instant stiffening of the projected concrete.

2.3.2 Application of sprayed concrete

Sprayed concrete, or more precisely the precursor of the dry mixing method under the name *gunite,* was invented over a century ago [27]. However, it was first during the last 30 years that this type of concrete gained attention as more research has been undertaken, new materials have been developed and contractors actively have been promoting the use of sprayed concrete [27].

Sprayed concrete was first used as a construction material for repairing damaged buildings [27]. In the more recent years, sprayed concrete is still used for repair work, but the application of this type of concrete has shifted towards concrete structures with complex geometry for which are too demanding for conventional cast methods [27]. In Norway, sprayed concrete is nowadays predominantly used for rock- and slope stabilization in tunnels and other underground constructions [18].

2.3.3 Mix design of sprayed concrete

Sprayed concrete used for rock- and slope stabilization is specified as *designed concrete* [23], that is, concrete for which required properties and additional characteristics, if any, are specified by the client and fulfilled by the producer [29]. In practice, both the producer and the contractors are responsible for ensuring that these specifications are met. These specifications include at least the following elements [23]:

- Strength class: B30/B35/B45
- Durability class: M40/M45/M60
- Toughness/energy absorption class: E500/E700/E1000
- Execution class
- Thickness or other geometry or quantity specifications

In addition to the specifications given by the client, the orderer must specify to the producer the following elements [23]:

- The w/c ratio at delivery, margin for water in the accelerator and if applicable, other admixtures to be added on site
- The temperature of fresh concrete at delivery (will be addressed in Chapter 3)
- The concrete workability at delivery (will be addressed in Chapter 3)

Since sprayed concrete is specified as designed concrete, there is a great variety in mix design for sprayed concrete. The choice of type and quantity of constituents varies from producer to producer and is based on both technical and economical considerations. A short introduction to the most common constituents in the basic mix will be given in the next section, before summarizing with a comparison between the mix design of basic mixes and the mix design of conventional concretes. It is important to stress the fact that accelerators, which are not included in the basic mix, still have to be considered in the mix design of basic mixes because of their high water content and thus their influence on the w/c ratio.

2.3.3.1 The constituents in sprayed concrete

The most common constituents in the basic mix are described below.

Cement

All cement types that are allowed to be used in conventional concrete are also qualified for use in sprayed concrete [23]. The amount of cement lies normally in the range 450 – 500 kg/m^3 [23]. The choice of type of cement is predominantly based on the requirements on early age strength [23], whereas the choice of quantity of cement is governed by the specified strength- and durability class, as well as requirements on workability properties in relation with water demand and aggregates properties.

Silica fume
A minimum dosage of silica fume of 4 % by cement weight is required [23]. According to NS-EN 206 [29], a content of silica fume up to 11 % by cement weight can be taken into account in the mass ratio. For common strength- and durability classes for sprayed concrete, the efficiency coefficient *k* for silica fume is 2 [23].

The application of silica fume in sprayed concrete is of significant importance for the properties of concrete in both the fresh and hardened state. Silica fume improves the fresh concrete properties in terms of increased flowability and improved adhesion properties [23]. Secondary beneficial outcomes include limited damages on machinery parts, reduced risk of blockage in the feed line, improved bonding to fibres and substrate, and less rebound during spraying [23]. Moreover, the application of silica fume results in improved strength and higher density, and thus providing a more durable concrete [23].

Aggregates
Aggregates with a maximum nominal grain size of 8 mm are required [23]. The aim of this requirement is to reduce rebound, to avoid voids on finished surfaces and to prevent blockage in feed lines during pumping [23]. Figure 2.18 shows the recommended grading limits given by NB7 [23].

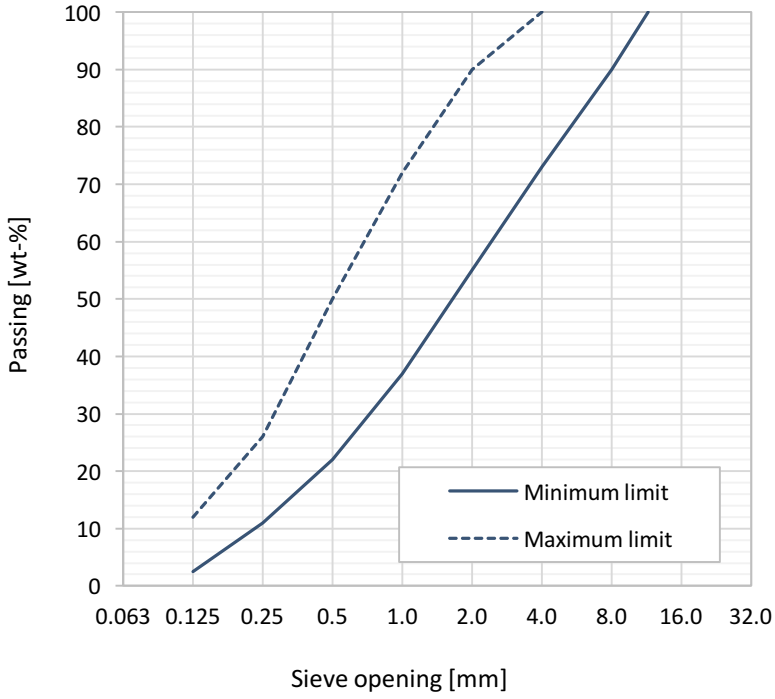


Figure 2.18: The grading limits for sprayed concrete. Figure after [23] (modified).

Fibres
The application of fibres is aimed at providing the hardened concrete fraction toughness [23]. However, fibres will only improve the fraction toughness of concrete up to a certain point as an excessive amount of fibres will cause compaction problems and consequently lower the fraction toughness. The recommended maximum content of fibres depends on the fibre length; increasing with decreasing length [23]. The presence of fibres will affect the fresh concrete properties negatively by decreasing the flowability (slump) of concrete [23]. This negative effect can be compensated with a higher matrix volume.

Two different types of fibres can be used in sprayed concrete; *steel fibres* and *polymer macro fibres* [18] [23]. For environmental reasons, the use of polymer macro fibres is not recommended and NPRA has just abandoned the use of this type of fibre in their road tunnel projects [30]. Some *polymer micro fibres* are also used in sprayed concrete, but these are added only to increase the resistance against spalling during fire [23].

Admixtures
The most important admixtures beside accelerators are listed below.

Polymer-based superplasticizers
These admixtures are used to improve the flowability of the basic mix [18]. Hence, the application of these admixtures is decisive to obtain a basic mix with desired workability.

Air entraining admixtures
These admixtures improve the flowability of the basic mix by introducing air voids and can therefore to a certain extent limit the use of superplasticizers [23]. It is important to keep in mind that the entrained air voids will be destroyed during spraying. Hence, a high content of air voids in the basic mix, will not necessary imply a high content of air voids in the hardened concrete.

Sprayed concrete retarders
These admixtures delay the hydration process in the basic mix until accelerators are added during spraying [23]. This type of admixture is aimed at preventing the basic mix from setting during transport, which is especially important for transport with long duration [23].

Internal curing admixtures
These admixtures provide beneficial curing conditions for the concrete after spraying without use of membrane or watering [23]. The application of these admixtures gives the basic mix improved adhesion properties and the hardened concrete lower permeability [23].

Pump aiding admixtures
These admixtures are similar to the stabilizing admixtures for conventional concrete. This type of admixture improves the pumpability properties of the basic mix and is usually applied when the pumping distance and/or the pumping pressure are significant and when crushed aggregates are used [23].

2.3.3.2 Sprayed concrete vs conventional concrete

The most important differences in mix design between sprayed concrete and conventional concrete are summarized in Table 2.1. The difference in w/c ratio is drawn based on concretes with durability class M45.

Table 2.1: The main differences between sprayed concrete and conventional concrete mix design.

Parameter	Sprayed concrete	Conventional concrete	Comments
w/c ratio	0.42	0.45	The lowered w/c ratio of sprayed concrete takes into account the additional water from accelerators.
Aggregates	max. 8 mm [23]	max. 16 – 32 mm [29]	The stricter requirement for sprayed concrete is aimed at preventing blockage in the feed line and to reduce rebound.
Cement	450 – 500 kg/m^3 [23] min. 300 kg/m^3 [a)] [29]	300 – 400 kg/m^3 [7] min. 300 kg/m^3 [a)] [29]	The cement content is higher in sprayed concrete due to the higher sand- and fines content (higher water demand).
Silica fume	min. 4 % [23] max. 11 % [23]	3 – 5 % [18]	The application of silica fume is more pronounced in sprayed concrete. The aim is to lower the cement content and to improve the stability of the basic mix.
Super-plasticizers	present	present	Superplasticizers are used in sprayed concrete to improve the mobility of the basic mix.
Air entraining admixtures	present	present[b)]	Air entraining admixtures are used in sprayed concrete for the same reasons as for superplasticizers.
Pump aid admixtures	present	present[c)]	Pump aid admixtures are used in sprayed concrete to obtain sufficient pumpability.
Fibres	present	present[d)]	The application of fibres is aimed at improving the toughness of the hardened concrete. The presence of fibres will affect the mobility of the basic mix negatively.

[a)] refers to the effective cement content = c + (k_{sf} × sf) + (k_{fa} × fa) + (k_{ggbs} × ggbs)
[b)] used in frost resistant concretes; min. 4 volum-% for MF45 [29]
[c)] can be used in concretes that need to be pumped over long distances
[d)] used in flooring concretes

3 EXPERIMENTAL PROGRAM

3.1 Materials

3.1.1 Cement and cementitious additives

The cement Standardsement FA (CEM II/B–M 42.5 R) by Norcem AS and the silica fume Elkem Microsilica 940U by Elkem AS have been used in this study. The chemical composition and the physical properties of these products are presented in Table 3.1 and Table 3.2, respectively. The given data is based on quality test and chemical analysis performed by the producers. Values in parentheses are the typical values given in the product data sheets.

Table 3.1: The chemical composition of the cement and the silica fume used in this study, given in wt-%.

Oxide	**Standardsement FA**[a)]	**Elkem Microsilica**[b)]
SiO_2	25.95	96.45
Al_2O_3	7.97	0.35
Fe_2O_3	4.00	0.11
CaO	51.30	0.26
K_2O	1.19	0.76
Na_2O	0.60	0.16
MgO	2.26	0.33
TiO_2	0.39	0.002
P_2O_5	0.22	0.09
SO_3	3.29	0.09
C	0.62	0.60
Mn_2O_3	0.057	-
$Na_2O_{eq.}$	1.38	-
Fly ash	18.2 (18)	-
Limestone	3.60 (4)	-
Free lime	1.68	-
Clinker	(78)	-

[a)] Data provided by Norcem AS.
[b)] Data provided by Elkem AS.

Table 3.2: The physical properties of the cement and the silica fume used in this study.

Property	**Standardsement FA**[a)]	**Elkem Microsilica**[b)]
LOI	3.01 %	0.90 %
Specific weight	(3000 kg/m^3)	(2200 kg/m^3)
Fineness (Blaine)	456 m^2/kg (450 m^2/kg)	-

[a)] Data provided by Norcem AS.
[b)] Data provided by Elkem AS.

3.1.2 Admixtures

Superplasticizing admixture of the type Sika SSP 2000 by Sika Norge AS has been used in this study. Some relevant information about this product is presented in Table 3.3. The given data has been provided by the producer.

Table 3.3: Product information of the superplasticizer used in this study.

Specific weight[a)]	Dry matter content	pH	Normal dosage
1055 kg/m^3	25 %	6.5	0.5 – 2.0 % by cement weight

[a)] Density in wet state.

3.1.3 Aggregates

In total five different types of sand materials from three different sources have been investigated in this study. The most essential information about these materials is summarized in Table 3.4. Keep in mind that not all five sand materials are involved in the study of concrete rheology; those materials investigated in the concrete rheology study are marked with a star *.

Table 3.4: General information about the sand materials investigated in this study.

				Production process		
Name	**Source**	**Particle sizes**	**Type of aggregate**	**Main process**	**Secondary process**	**Rock types**
MR1*	Årdal	0 – 8 mm	Natural	Glaciofluvial and moraine deposit	Partly crushed Washed	Dark rocks Granite/gneiss Feldspathic rocks
MR2	Årdal	4 – 8 mm	Natural	Glaciofluvial and moraine deposit	Partly crushed Washed	Dark rocks Granite/gneiss Feldspathic rocks
MF *	Follo Line	0 – 8 mm	Crushed	Tunnelling TBM	Crushed Washed	Granite/gneiss
MU1*	Ulriken	0 – 4 mm	Crushed	Tunnelling D&B	Crushed Washed	Dark rocks Granite/gneiss Feldspathic rocks
MU2	Ulriken	0 – 4 mm	Crushed	Tunnelling D&B	Crushed	Dark rocks Granite/gneiss Feldspathic rocks

Three of these sand materials are processed excavated rock materials from two ongoing tunnelling projects in Norway (per June 2017), the new Ulriken tunnel and the Follo Line tunnel, where NCC and AGJV, respectively, are the companies responsible for the processing of the rock materials. Furthermore, the 0 – 8 mm natural sand material from Årdal, which is much used as concrete aggregates today, has been included in this study as a reference material. The 4 – 8 mm natural sand material from Årdal has been used to a limited extent to ensure that all the sand materials involved in the concrete rheology study are similarly graded (will be described in detail later). The supplier of the natural sand materials is NorStone AS.

The natural sand materials from Årdal, MR1 and MR2, are partly processed in terms of crushing and cubisizing of particles larger than 22 mm and washing [31]. In fact, the term *natural-crushed sand* is more precise to use about these sand materials. It is however assumed that the proportion of crushed particles in these materials is rather small and that the effect of these particles on the fresh concrete properties is negligible. The sand materials from Ulriken, MU1 and MU2, are crushed from the larger rock fragments that are produced from the traditional tunnelling method *Drilling and Blasting* (D&B). The crushing process includes a jaw crusher in the primary stage, a gyratory crusher in the secondary stage and a cone crusher in the tertiary stage [32]. The sand material from the Follo Line, MF, is produced by crushing the products of the *Tunnel Boring Machine* (TBM), also called TBM muck, into smaller particles[5]. The crushing process includes a cone crusher in the tertiary stage and a VSI in the quaternary stage [33]. Crushers in the primary- and secondary stage are not necessary as the TBM muck contains rock fragments with sizes up to approximately 150 mm only. In fact, only the fraction 20 – 100 mm is further processed and used for the production of the sand material [33].

The sand materials are composed of similar rock types; primarily dark rocks, granite, gneiss and feldspathic rocks. The rock types making up MR1 and MR2 have been declared by NorStone AS. The papers in which these are declared is found in Appendix A.1. The rock types in MU1, MU2 and MF1, on the other hand, have been characterized by SINTEF. The characterization was based on visual examination, supplemented by examination with a stereomicroscope.

[5] The author was informed at a late stage of the study that the crushed sand material from the Follo Line, MF, *might* have been blended with some natural sand. This information has not been taken into consideration in this study.

3.2 Study of geometrical properties – Characterization of aggregates

Only the properties that are considered as relevant for this study have been characterized and included. These properties are presented in Table 3.5 along with the documents in which the standard methods for characterizing these properties are described. Grading, fines content, particle shape, free mica content and specific surface area are properties that are known to have an impact on the fresh concrete properties, whereas particle density and water absorption are properties that are necessary for the proportioning of concrete. The requirements related to these properties, enforced by the European Committee for Standardization (NS-EN standards) and NPRA (handbook R762), are also presented. The stricter requirements given by NPRA are not absolute and are only valid when the project owner or engineers requires so.

Table 3.5: The characterized properties and the associated documents in which the standard characterization methods for these properties are described.

		Requirements according to	
Property	**Reference**	**NS-EN standard**	**Handbook R762 [34]**
Grading	NS-EN 12620 [20] NS-EN 933-1 [35] NS-EN 933-10 [36]	-	-
Fines content	NS-EN 12620 [20] NS-EN 933-1[35]		Max. $f_{1.5}$ for coarse aggregates [a)1)]. Max. f_{10} for 0 – 8 mm natural graded aggregates[b)1)].
Particle density	NS-EN 12620 [20] NS-EN 1097-6 [37]	-	Must conform to the regulations of concrete density.
Water absorption	NS-EN 12620 [20] NS-EN 1097-6 [37]	-	Max. 1.2 % for aggregates > 8 mm. Max. 1.5 % for aggregates < 8 mm.
Particle shape	NS-EN 933-3 [38] NS-EN 933-4 [39] Kontrollrådet's characterization method [40]	Max. FI_{35} for natural coarse aggregates[a)2)] [38].	Max. FI_{20} for coarse aggregates [a)2)].
Free mica content	NS-EN 12620 NPRA's handbook R210 [41]		Max. 20 % in the fraction 0.125 – 0.250 mm.
Specific surface area	-	-	-

[a)] Coarse aggregates refer to aggregates with $D \geq 4$ mm and $d \geq 2$ mm.
[b)] Natural graded aggregates refer to 0 – 8 mm natural or natural/crushed aggregates.
[1)] Max. f_{xx} = fines content ≤ XX %.
[2)] Max. FI_{xx} = flakiness index ≤ XX %.
- Not specified.

The characterization of the crushed sand materials could have also included the alkali-reactivity, the chloride content, the sulphate content and the total sulphur content. These properties can be decisive for whether or not the excavated rock materials can be used as concrete aggregates. However, as mentioned initially in this thesis, only the geometrical properties will be focused on in this study and thus the chemical properties will not be investigated here.

Table 3.6 shows who has been responsible for the characterization of the different properties for the different materials. Product documentation papers including CE-marking and declaration of conformity (DoP) from NorStone AS can be found in Appendix A.1. The methods that have been applied by SINTEF for the characterization will be described in detail in the following sections.

Table 3.6: Declaration of the different properties.

	MR1	**MR2**	**MF**	**MU1**	**MU2**
Grading	N	N	S	S	S
Fines content	N	N	S	S	S
Particle density	N	N	S	S	-
Water absorption	N	N	S	S	-
Particle shape	S	-	S	S	-
Free mica content	S	-	S	S	-
Specific surface area	S	-	S	S	-

S Property characterized by SINTEF.
N Property declared by NorStone AS.
- Property not characterized.

Not all properties have been characterized for MR2 as only a small amount of this material has been used and its effect on the fresh concrete properties is therefore assumed to be negligible. Only the grading and the fines content have been characterized for MU2. The other properties, except for the specific surface area, are assumed to be approximately the same as those of MU1. The specific surface area of MU2 was not characterized as this material is not included in the study of concrete rheology.

3.2.1 Grading

Mechanical sieve analysis is the most commonly used method to establish the grading of aggregates. However, for the grading of the finest particles, other methods, e.g. *air jet sieve analysis*, *Coulter analysis* or *Sedigraph analysis*, must be applied. Note that the grading of particles finer than 0.063 mm cannot be determined by the standardized air jet sieve analysis described in NS-EN 933-10 [36]. The Coulter analysis and the Sedigraph analysis, on the other hand, are both suitable for this purpose. An evaluation of the reliability of the two latter methods along with several other methods can be found in Cepuritis' doctoral thesis [1]. In this study, the choice of methods for determining the grading of the different sand materials was based on common practice and availability. The grading curves were obtained by performing

the wet mechanical sieve analysis and the Coulter analysis. The latter method was only performed on the fines (particles ≤ 0.125 mm) of MR1, MF and MU1, as only these sand materials are included in the study of concrete rheology.

The wet mechanical sieve analysis is described in NS-EN 933-1 [35]. Before sieving, the weight of each sample in dry condition, M_1, was measured and recorded. The samples were washed in order to remove particles ≤ 0.063 mm and then dried at 105 °C for minimum 24 h. The weight of each sample after washing, drying and cooling, M_2, was measured and recorded. Thereafter, the samples were sieved mechanically through a column of sieves with descending aperture sizes from the top to the bottom. The column consisted of a pan, a lid and sieves with the following aperture sizes: 0.063, 0.125, 0.250, 0.5, 1, 2, 4 and 8 mm. The grading curves were finally obtained by summing up the mass retained in each sieve successively, commencing with the sieve with the largest aperture size, and dividing by the original dry weight, M_1.

The Coulter analysis is based on laser diffraction. The instrument used for the analysis, Coulter LS 230, measures the diffraction of light on particles and as the level of diffraction varies with the particle volume, the particle size distribution can be determined [42]. The instrument can measure particle sizes in the range 0.04 – 2000 μm [42]. In this study, the Coulter analysis was used to establish the grading of the particles in the 0 – 0.125 mm fraction.

Neither the NS-EN standards nor NPRA's handbook R762 regulates the grading of aggregates. However, as already addressed in section 2.2.2.2, a "smooth" or dense grading curve is beneficial for the workability of fresh concrete, especially for concrete that needs to be pumped, and should therefore be kept in mind when proportioning concrete. The grading limits for sprayed concrete is provided in NB7 [23] (see section 2.3.3.1).

3.2.2 Fines content

The determination of the fines content of the different sand materials was incorporated in the wet mechanical sieve analysis. According to NS-EN 933-1 [35], the fines content of a given sample is defined as the percentage of particles passing the 0.063 mm sieve and can simply be calculated from the following equation:

$$f = \frac{(M_1 - M_2) + P}{M_1} \cdot 100$$

where

- f - fines content [%]
- M_1 - dried mass of the origin sample [kg]
- M_2 - dried mass of the sample after washing, drying and cooling [kg]
- P - mass of the screened material remaining in the pan[6] [kg]

It is important to keep in mind that fines are sometimes referred to as particles ≤ 0.125 mm due to the implementation of the PM model (see section 2.1.3).

[6] Note that some of the particles ≤ 0.063 mm remain in the sample after washing. P is therefore included in the equation.

Today, the fines content is not regulated by the NS-EN standards. NPRA, on the other hand, has enforced an upper limit of 1.5 % for coarse aggregates and 10 % for natural graded aggregates [34]. The maximum fines content for crushed aggregates is not specified, but the content should not be too high as it may affect the workability of concrete negatively. In this study, crushed sand with a fines content of more than 10 % will be regarded as high and unfavourable. It is important to keep in mind that even though a lower limit is not specified, a certain fines content is desired (see section 2.2.2.3).

3.2.3 Particle density and water absorption

The particle density and the water absorption were determined by means of the *Pyknometer method,* which is described in NS-EN 1097-6 [37]. Only the 0.063 – 4 mm fraction was considered in this method.

Before testing, each sample was sieved and washed to remove excessive particles (≤ 0.063 mm and > 4 mm). Thereafter, four parameters, M_1, M_2, M_3 and M_4, were determined for each sample by means of the following steps:

1. The sample was immersed in water with a constant temperature of approximately 22 °C in a glass container (pyknometer) for minimum 24 h.
2. Additional water was added into the container until it was entirely filled. The weight of the container with the sample, entirely filled with water and covered with a glass plate, M_2, was measured and recorded.
3. The sample was removed from the container. The weight of the container entirely filled with water and covered with a glass plate, M_3, was measured and recorded.
4. The sample was dried gently and uniformly by warm air until the surface dry state was reached. To check whether the surface dry state was reached or not, an open-ended metal cone mould (dimensions given in the standard), placed with the largest diameter face downwards, was filled with the sample. After tampering the sample inside the mould 25 times with a metal rod, the mould was gently lifted. When the remaining sample totally collapsed, the surface dry state was considered as reached. The weight of the surface-dried sample, M_1, was measured and recorded.
5. The sample was dried at 105 °C for minimum 24 h. The weight of the sample after drying and cooling, M_4, was measured and recorded.

Finally, the particle density and the water absorption of each sample were determined based on the following equations:

$$\rho_{ssd} = \frac{M_1}{M_1 - (M_2 - M_3)}$$

$$WA = 100 \cdot \frac{(M_1 - M_4)}{M_4}$$

where

M_1 - weight of the saturated and surface-dried sample [g]
M_2 - weight of the container with the sample, filled entirely with water and covered with a glass plate [g]
M_3 - weight of the container filled entirely with water and covered with a glass plate [g]
M_4 - weight of the oven-dried sample [g]
ρ_{ssd} - particle density of the saturated and surface-dried sample [Mg/m^3].
WA - water absorption after immersion for minimum 24 h [wt-% of oven-dry material]

The particle density and the water absorption are only regulated by NPRA. NPRA requires that the particle density conforms to the regulations of the concrete density, which depend among others on the type of concrete and the load capacity of the construction [29] [34]. For Norwegian aggregates, the particle density normally lies in the range 2600 – 2900 kg/m^3 [18].

The water absorption influences the water demand of concrete [7]. Use of aggregates with high water absorption can therefore have a negative impact on the fresh concrete properties. Hence, NPRA requires that the water absorption is maximum 1.2 % for aggregates coarser than 8 mm and maximum 1.5 % for aggregates finer than 8 mm [34]. The water absorption for Norwegian aggregates lies normally in the range 0.3 – 0.8 % [7]. Natural aggregates have typically values around 0.5 %, whereas crushed aggregates have somewhat higher values [43].

3.2.4 Particle shape

The characterization of particle shape of aggregates involves the study of geometrical properties, such as *angularity, flakiness* and *elongation.* For particles greater than 4 mm, the characterization is performed in accordance to NS-EN 933-3 [38] and NS-EN 933-4 [39]. In these standards, the particle shape quality is described with the *flakiness index* and the *shape index*. For particles smaller than 4 mm, on the other hand, the characterization is not standardized. Various methods can be used to describe the particle shape quality, e.g. *F-shape determination test, rheology test, μCT & SH method* or *DIA method* [1] [26].

In this study, a simple test method described in *Metoder for prøving av betongtilslag* written by Kontrollrådet [40] was used to characterize the particle shape of the sand materials. This method involved visual assessment and manual measurement of small representative portions of the sand materials. Approximately 150 randomly selected grains from each of the fractions 2 – 4 mm and 4 – 8 mm were assessed. The particle shape quality of each fraction was determined and expressed as the number of flaky and elongated particles in percentage of the total number of assessed particles. The following definitions were adopted in this method:

Flaky grains: $\frac{\text{width}}{\text{thickness}} \geq 2.0$

Elongated grains: $\frac{\text{length}}{\text{thickness}} \geq 2.5$

Cubical grains: otherwise

As addressed in section 2.2.2.4, the particle shape of aggregates has a great impact on the workability properties of concrete. Unfortunately, both the NS-EN standards and NPRA's handbook R762 provide limit values in terms of flakiness indices and thus these limits apply only for aggregates coarser than 4 mm. For finer aggregates, a content of flaky and elongated particles greater than approximately 40 % can be considered as poor shape quality [7] [43].

3.2.5 Free mica content

The content of free mica was determined by the simple test method described in NPRA's handbook R210 *Laboratorieundersøkelser* [44]. A small sample containing particles in the 0.125 – 0.250 mm fraction was placed and glued on a millimetre paper and examined visually with a stereomicroscope. The content of free mica was determined as the number of counted mica minerals in percentage of the total number of counted grains.

The content of free mica represents an important influence on the water demand of concrete [7]. However, the content of this type of minerals is not regulated by the NS-EN standards. A content of free mica greater than 10 – 15 % is regarded as relatively high [7]. NPRA operates with a upper limit of 20 % [34].

3.2.6 Specific surface area

Given that all particles are spherical, the specific surface area of aggregates can be easily estimated based on knowledge of the grading [21]. However, this method is a rough approximation for crushed aggregates as their particles typically are flaky and elongated, and should therefore be supplemented with other methods or substituted by more accurate approaches.

In this study, the specific surface area of the fines (particles ≤ 0.125 mm) of MU1, MF and MR1, was determined by performing the *BET (Brunauer-Emmett-Teller) analysis*. The instrument used is the FlowSorb II 2300. This analysis is based on the principle of physical adsorption of gas molecules on solid material surfaces. By measuring the amount of adsorbed nitrogen gas at -196 °C for different N_2 partial pressures, the specific surface area can be calculated [45]. This method measures all surfaces including pores, internal surfaces and micro-cracks [45], and will therefore provide higher values compared to the aforementioned calculation method based on aggregate grading, which only takes into account the external surfaces of aggregate particles.

3.3 Study of concrete rheology – Characterization of basic mixes

In the study of concrete rheology, the performance of the crushed sand materials MF and MUI (+MR2) in fresh concrete was investigated in comparison with the reference sand material MR1. The study involves three main basic mixes; one reference mix with pure natural sand (MR1) and two mixes with partly natural sand (MR1) and crushed sand (MF, MU1+MR2). These mixes are further denoted as mix MR100, mix MF50 and mix MU50. All of them were proportioned for a compressive strength class of B35 and a durability class of M45. Except for the type of aggregate, the same mix design was applied for all three mixes.

The mix design of the basic mixes was primarily based on a standard mix design used for tunnel lining, provided by a Norwegian commercial ready-mix concrete supplier. Moreover, the mix design of the basic mixes was ensured to meet the requirements given in NB7 [23] and NS-EN 206 [29]. These requirements along with the references where these are described are shown in Table 3.7. Requirements related to the chemical properties, e.g. content of chlorides and content of alkalis, were not included in this study.

Table 3.7: Requirements for the mix design of sprayed concrete.

Parameter	**Value**	**Reference**
Min. silica fume	4 wt-% of cement	NB7 [23], 1.3.2
Max. w/c ratio	0.450	NS-EN 206 [29], NA.5.3.2
Min. binder[a)] content	300 kg/m^3	NS-EN 206 [29], NA.5.3.2
Max. fly ash/cement-ratio	0.350	NS-EN 206 [29], NA.5.2.5.2.1
Max. silica fume/cement-ratio	0.110	NS-EN 206 [29], NA.5.2.5.2.3

[a)] Binder = cement + Σ(k · additive)

The PM model has been implemented in this study. The properties of the particle phase and the matrix phase of each basic mix have been characterized by means of the void content test and FlowCyl test, respectively.

As will be discussed in chapter 4, the results of the void content test, which will be introduced in section 3.3.1, show that the amount of voids in the particle phase increases with increasing proportion of crushed sand. In order to keep the void content of the particle phase low, but still be able to detect the effect of the properties of crushed sand on the fresh concrete properties, the two basic mixes with crushed sand, MF50 and MU50, were designed with 50 % crushed sand and 50 % natural sand by mass. This choice was also based on what is appropriate to do in practice. To be able to compare the three basic mixes, MU1 and MR2 were combined such that the entire particle size range of interest (0 – 8 mm) was covered. The proportion between these materials was 90 wt-% MU1 and 10 wt-% MR2.

The mix design of the basic mixes was based on a superplasticizer content of 0.8 % by binder weight, which lies in the typical range for sprayed concrete with natural aggregates. In practice, the dosage of superplasticizer was evaluated and determined for each mix during mixing. Superplasticizer was added into the fresh mix sequentially until a desired consistence was achieved, i.e. a slump of 220 – 240 mm.

After the main basic mixes were tested and evaluated, it was decided that a fourth basic mix should be tested. The aim of the fourth mix, MU100, is to give a better understanding of the effect of the typical properties of crushed sand, in this case a high proportion of irregularly shaped particles.

The mix design of all four basic mixes are summarized in Table 3.8. More details can be found in Appendix A.2. Skanska's Excel spreadsheet was used for the proportioning of the basic mixes. The volume of each mix was 30 litres. The basic mixes might have been slightly optimistic as fibres, which may have a negative effect on the fresh concrete properties (see section 2.3.3.1), were not included. However, this might have been compensated to a certain extent by excluding air entraining admixtures and pumping improvers, which are normally used in sprayed concrete to improve its workability/pumpability properties.

Table 3.8: The mix design of the four basic mixes.

	MR100 (reference)	**MF50**	**MU50**	**MU100**
	Proportion			
Designed w/c_{eq} [a)] ratio	0.42			
Matrix volume	430 l/m^3			
Dosage of sf	9.0 % by binder weight			
Aggregate composition	100 % MR1	50 % MR1 50 % MF	50 % MR1 45 % MU1 5 % MR2	100 % MU1
Dosage of SP	0.62	0.72	0.63	0.80
	Quantity [kg/30 litre]			
Cement	13.403	13.335	13.282	13.147
Silica fume (k=2)	1.326	1.319	1.314	1.300
Mixing water[b)]	5.126	5.206	5.210	4.989
MR1	47.935	24.392	25.163	-
MR2	-	-	2.448	5.143
MU1	-	-	22.494	47.672
MF	-	24.252	-	-
Superplasticizer	0.0907	0.1050	0.0915	0.115

[a)] w/c_{eq} = water/(cement + Σ(k · additive))
[b)] Corrected for absorbed water and free surface moisture in the aggregates, as well as the water content in SP

3.3.1 Particle phase testing – Void content test

The aim of the void content test is to find appropriate aggregate compositions for the basic mixes. Hence, different aggregate compositions with different proportions of crushed aggregates have been investigated in order to find the compositions giving optimal particle packing densities, i.e. minimum void contents, if any exist.

3.3.1.1 Composition of test samples

The void content of the particle phase was determined for the aggregate compositions presented in Table 3.9. The particle phase compositions related to these aggregate compositions are slightly different. For simplicity, the difference was neglected and the composition of the aggregates and composition of the equivalent particle phases were considered the same.

The void content of each particle phase composition was calculated by taking the mean value of three representative measurements, that is, three test samples were prepared and tested for each particle phase composition. The determination of void content was based on dry test samples as this is the easiest way to ensure small variation in the moisture condition among the test samples. Furthermore, the test samples were loosely packed as this condition better reflects the real situation.

An Excel spreadsheet has been created to prepare the test samples. The spreadsheet is presented in Appendix A.3 (page 1).

Table 3.9: The aggregate compositions for which the void content was determined.

No.	Aggregate composition[a)] [wt-% of total mass]			No.	Aggregate composition [wt-% of total mass]	
1	100 % MR1	0 % MU1	0 % MR2	12	100 % MR1	0 % MF
2	90 % MR1	9 % MU1	1 % MR2	13	90 % MR1	10 % MF
3	80 % MR1	18 % MU1	2 % MR2	14	80 % MR1	20 % MF
4	70 % MR1	27 % MU1	3 % MR2	15	70 % MR1	30 % MF
5	60 % MR1	36 % MU1	4 % MR2	16	60 % MR1	40 % MF
6	50 % MR1	45 % MU1	5 % MR2	17	50 % MR1	50 % MF
7	40 % MR1	54 % MU1	6 % MR2	18	40 % MR1	60 % MF
8	30 % MR1	63 % MU1	7 % MR2	19	30 % MR1	70 % MF
9	20 % MR1	72 % MU1	8 % MR2	20	20 % MR1	80 % MF
10	10 % MR1	81 % MU1	9 % MR2	21	10 % MR1	90 % MF
11	0 % MR1	90 % MU1	10 % MR2	22	0 % MR1	100 % MF

[a)] MU1 and MR2 were combined such that the entire particle size range of interest (0 – 8 mm) was covered. The relative proportion between MUI and MR2 is 90 wt-% MU1 and 10 wt-% MR2.

3.3.1.2 Measurement and calculation of the void content

The void content, v, is calculated from the bulk density of the particle phase, ρ_b, and the density of the particles, ρ_p. The procedure for determining the loose bulk density and the void content is described in NS-EN 1097-3 [46], whereas the procedure for determining the particle density is described in NS-EN 1097-6 [37] (see section 3.2.3). The apparatus used for determining the loose bulk density and the void content is shown in Figure 3.1 (left).

Before measuring the loose bulk density, each test sample was prepared, which included drying in the oven at 105 °C for minimum 24 h, sieving in order to remove all particles ≤ 0.125 mm, combining the different sand materials according to the specified compositions in Table 3.9 and homogenizing by the aid of a large bucket with lid. For each measurement, the test sample was reduced into an appropriate size (enough mass to fill the container) with a sample splitter. Thereafter, the test sample was transferred into a container until the container was entirely filled. A plastic cylindrical container with weight 1312 g and volume 4.9 l was used. The dimensions of the container are shown in Figure 3.1 (right). Removal of excessive material and levelling of the surface were carefully executed to avoid compaction of the test sample. Finally, the weight of the container with the test sample was measured and recorded.

The calculation of the loose bulk density and the corresponding void content was based on the following equations:

$$\rho_b = \frac{m_2 - m_1}{V}$$

$$v = \frac{\rho_p - \rho_b}{\rho_p} \cdot 100$$

where

v	-	void content [%]
ρ_b	-	loose bulk density [Mg/m^3]
ρ_p	-	particle density [Mg/m^3]
m_2	-	mass of the container with the test sample [kg]
m_1	-	mass of the container [kg]
V	-	volume of the container [l]

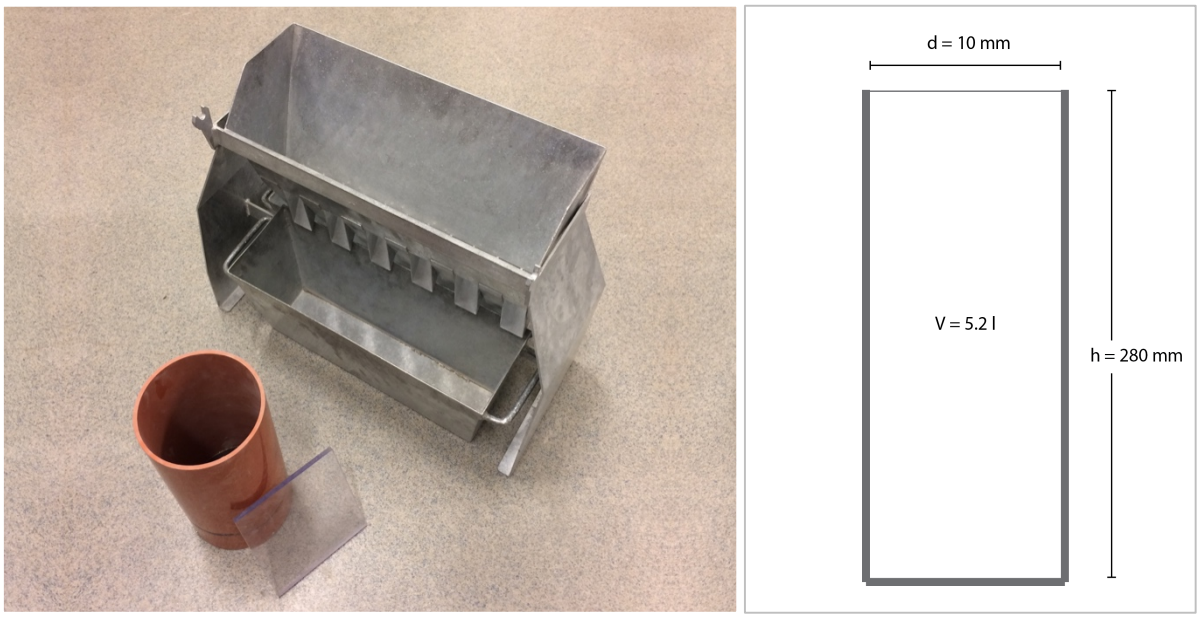


Figure 3.1: The apparatus used to measure the loose bulk density and the void content – The apparatus includes a riffle splitter, a cylindrical container and a glass plate for levelling (left). The dimensions of the cylindrical container (right).

3.3.2 Matrix phase testing – FlowCyl test

The properties of the matrix phase, i.e. the flow resistance, are characterized by means of the FlowCyl test [13] [14] [15] [17]. The aim of performing the FlowCyl test is to study the performance (with respect to the flow resistance) of the fines (particles ≤ 0.125 mm) of MR1, MF and MU1 in the matrix phase, and in this way establish a basis for predicting their influence on the fresh concrete properties. Two test series involving several mixes have been carried out. These will be further referred to as FlowCyl test series I and FlowCyl test series II. In FlowCyl test series I, the influence of superplasticizer on the flow resistance was studied by varying the dosage of superplasticizer whereas in FlowCyl test series II, the effect of surface area of fines on the flow resistance was studied by varying the fines/binder ratio (f/b ratio).

3.3.2.1 Composition of matrix materials

The FlowCyl test series I involved three different matrix materials, which are equivalent to the matrix phase of the three main basic mixes presented in section 3.3. Each of these matrix materials was tested for different dosages of superplasticizer, specifically 0.5 %, 0.75 %, 1.0 % and 1.5 % by binder weight. It is obvious that the quantity of the other constituents will vary slightly with the dosage of superplasticizer. The use of superplasticizer will contribute to increase the water content and the quantity of the other constituents must be adjusted accordingly to keep the w/c ratio constant. All the mixes that have been tested in this test series are presented in Table 3.10 on the next page. Only the aggregate composition, the fines/binder ratio and the dosage of superplasticizer related to each mix is presented. The complete composition of these mixes can be found in Appendix A.4. These compositions have been extracted directly from the mix design of the three main basic mixes presented in section 3.3, with varying superplasticizer contents.

In the FlowCyl test series II, three additional matrix materials were tested for different f/b ratios. In contrary to the matrix materials in the FlowCyl test series I, the fines in these matrix materials were not combined. All the mixes that have been tested in this test series are shown in Table 3.11 on the next page. The complete composition of these mixes is presented in Appendix A.4. These compositions were extracted from the mix design of three basic mixes containing pure MR1, MF and MU1, respectively, and with a constant superplasticizer content. To be able to see the effect of the different fines' properties on the matrix properties and at the same time avoid segregation, a superplasticizer content of 1.0 wt-% was chosen. The f/b ratio was varied by varying the content of fines (particles ≤ 0.125 mm).

Table 3.10: The mixes involved in the FlowCyl test series I.

Name	Aggregate composition[a) b)] [wt-% of total mass]			f/b ratio [-]	Dosage of SP [wt-% of binder content]
Mix $U1_I$	50 % MR1	45 % MU1	5 % MR2	0.23	0.5 %
Mix $U2_I$	50 % MR1	45 % MU1	5 % MR2	0.23	0.75 %
Mix $U3_I$	50 % MR1	45 % MU1	5 % MR2	0.23	1.0 %
Mix $U4_I$	50 % MR1	45 % MU1	5 % MR2	0.23	1.5 %
Mix $F1_I$	50 % MR1	50 % MF		0.21	0.5 %
Mix $F2_I$	50 % MR1	50 % MF		0.21	0.75 %
Mix $F3_I$	50 % MR1	50 % MF		0.21	1.0 %
Mix $F4_I$	50 % MR1	50 % MF		0.21	1.5 %
Mix $R1_I$	100 % MR1			0.19	0.5 %
Mix $R2_I$	100 % MR1			0.19	0.75 %
Mix $R3_I$	100 % MR1			0.19	1.0 %
Mix $R4_I$	100 % MR1			0.19	1.5 %

[a)] The aggregate compositions are related to the basic mixes, which have been used to determine the composition of the mixes.
[b)] MU1 and MR2 were combined such that the entire particle size range of interest (0 – 8 mm) was covered. The relative proportion between MUI and MR2 is 90 wt-% MU1 and 10 wt-% MR2.

Table 3.11: The mixes involved in the FlowCyl test series II.

Name	Aggregate composition[a)] [wt-% of total mass]	f/b ratio [-]	Dosage of SP [wt-% of binder content]
Mix $U1_{II}$	100 % MU1	0.10	1.0 %
Mix $U2_{II}$	100 % MU1	0.22	1.0%
Mix $U3_{II}$	100 % MU1	0.33	1.0 %
Mix $U4_{II}$	100 % MU1	0.45	1.0%
Mix $F1_{II}$	100 % MF	0.09	1.0 %
Mix $F2_{II}$	100 % MF	0.20	1.0%
Mix $F3_{II}$	100 % MF	0.29	1.0 %
Mix $F4_{II}$	100 % MF	0.39	1.0%
Mix $R1_{II}$	100 % MR1	0.09	1.0 %
Mix $R2_{II}$	100 % MR1	0.12	1.0%
Mix $R3_{II}$	100 % MR1	0.15	1.0 %
Mix $R4_{II}$	100 % MR1	0.29	1.0%

[a)] The aggregate compositions are related to the basic mixes, which have been used to determine the composition of the mixes.

3.3.2.2 Mixing procedure

Two different mixing procedures were utilized to prepare the mixes in the FlowCyl test series I. Blade type and rotational speed related to these procedures are presented in Table 3.12. A step-by-step description of the mixing procedures is given in Table 3.13 and Table 3.14.

Table 3.12: Blade type and rotational speed associated to the two mixing methods used in the study.

Mixer type	Blade type	Rotational speed [rpm]
Hobart mixer	Flat, steel (see Figure 3.2 B))	75 – 150 [47]
Drill mixer	Hollow, steel (see Figure 3.2 C))	1000 – 1850 [47]

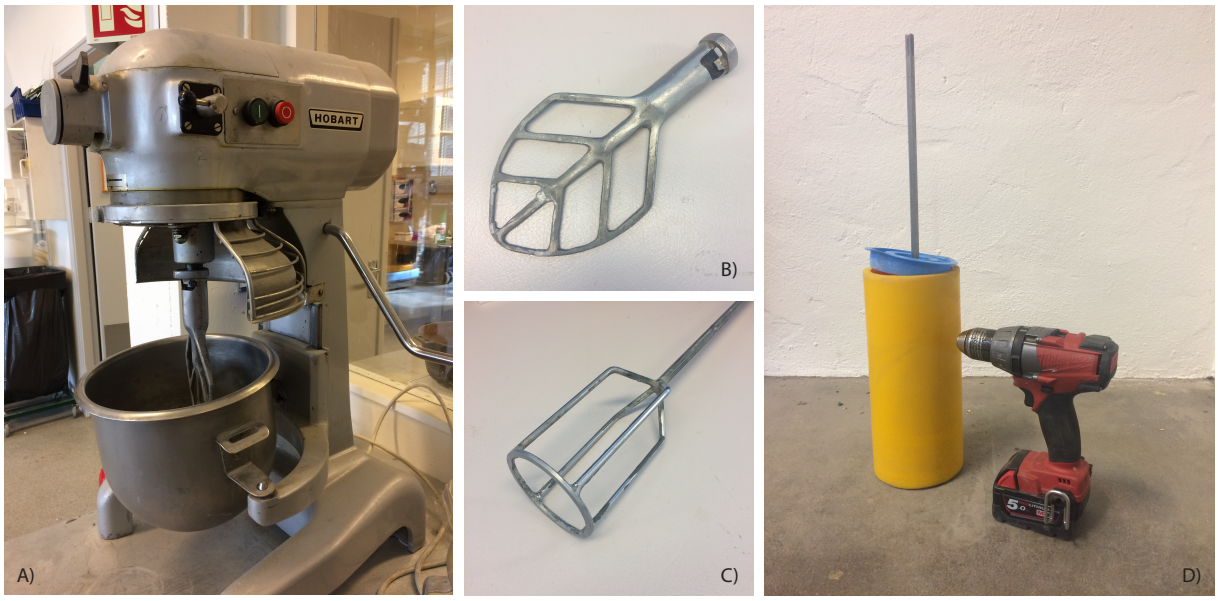


Figure 3.2: A) Mixing setup of the Hobart mixing method. B) Flat blade for the Hobart mixer. C) Hollow steal beater for the drill mixer. D) Mixing setup of the drill mixing method.

Initially, the procedure that involves a 5 litre Hobart mixer was chosen for practical reasons; is easy to handle the apparatus, requires minimal energy and can be performed by one person. Furthermore, the Hobart mixer is the standard mixer used for cement testing [48] and is widely used in concrete laboratories for research purposes. Figure 3.2 A) and B) show the Hobart mixer and the blade used for the mixing.

As the Hobart mixing method appeared to give abnormally high flow resistance values, another rather new mixing procedure was tested. According to earlier studies [12] [49] [50], the shear rate for which cement-based materials are subjected to during mixing is one of the most important parameters influencing their rheological properties. This statement is confirmed by the study carried out by Ng et al. [47], where three mixing setups were studied. The study revealed that among the investigated mixing procedures, the Hobart mixing method gave the highest flow resistance values, whereas the new mixing procedure, which was first introduced in this study, gave the lowest values.

The new mixing procedure involves a drill mixer, which is simply a steel beater attached to a handheld drill. The drill mixing method was developed specifically for the study of matrix materials, aimed to give a good correlation between the separately mixed matrix phase and the actual matrix phase of the concrete at an affordable price [47]. The method has been proven to give better results than the Hobart mixing method in terms of dispersion and homogeneity,

without excessive temperature rise and air entrainment [47]. However, the method is more energy requiring and difficult to perform alone. Hence, the original procedure, which can be found in the study of Ng. et al. [47], was slightly adjusted in order to make it easier for one person to perform it. The apparatus includes a handheld drill, a steal beater, a plastic cylindrical container with an inner height of 300 mm and an inner diameter of 110 mm and a purpose-made lid. Figure 3.2 C) and D) show the mixing setup of the drill mixing method and the steel beater used for the mixing.

Table 3.13: Step-by-step description of the Hobart mixing method.

Mixing step no.	Time after start[a)] [min]	Duration [min]	Action
			Dry mixing
1	-1	1	All dry constituents are mixed at low speed (speed 1).
			Wet mixing
2	0	2	Water and superplasticizer are added while the mixer is running. Mixing at low speed (speed 1).
3	2	1	Undispersed material is detached from the bowl's inner walls and bottom.
4	3	1	Mixing at medium speed (speed 2).
5	4	5	The mix is left at rest.
6	9	1	Mixing at medium speed (speed 2).
7	10	2	The mix is transferred into a suitable container and thereafter into the FlowCyl apparatus as described in section 3.3.2.3. Data recording starts 12 minutes after start[a)].

[a)] Start is defined as the point when the wet constituents are added into the Hobart mixer.

Table 3.14: Step-by-step description of the drill mixing method.

Mixing step no.	Time after start[a)] [min]	Duration [min]	Action
			Premixing
1	-2	2	All dry constituents are premixed in a Hobart mixer at low speed (speed 1).
2	-1	1	Water and superplasticizer are added into the purpose-made container further used for the wet mixing, whilst the Hobart mixer is still running.
			Wet mixing
3	0	4	The premixed dry constituents are transferred into the purpose-made container with a scoop and mixed carefully with the drill mixer or a spatula. This is done in two-three sequences to avoid overfilling. If necessary, undispersed material is detached from the inner walls.
4	4	2	Mixing at high speed.
5	6	2	The mix is left at rest.
6	8	2	Mixing at low speed.
7	10	2	The prepared mix is transferred into a suitable container and thereafter into the FlowCyl apparatus as described in section 3.3.2.3. Data recording starts 12 minutes after start[a)].

[a)] Start is defined as the point when the dry constituents are transferred into the purpose-made container.

Only the drill mixing method was used to prepare the mixes in the FlowCyl test series II.

3.3.2.3 Measurement of the flow resistance

Figure 3.3 shows the experimental setup of the FlowCyl test [13] [14] [15] [17]. The apparatus consists of a vertical cylindrical steel tube positioned on a rack and a steel container placed on an electronic scale, which is connected to a data recording computer. The steel tube has a total height and an inner diameter of 400 mm and 80 mm, respectively, and has a cone-shaped bottom ending in a small outlet with an inner diameter of 8 mm.

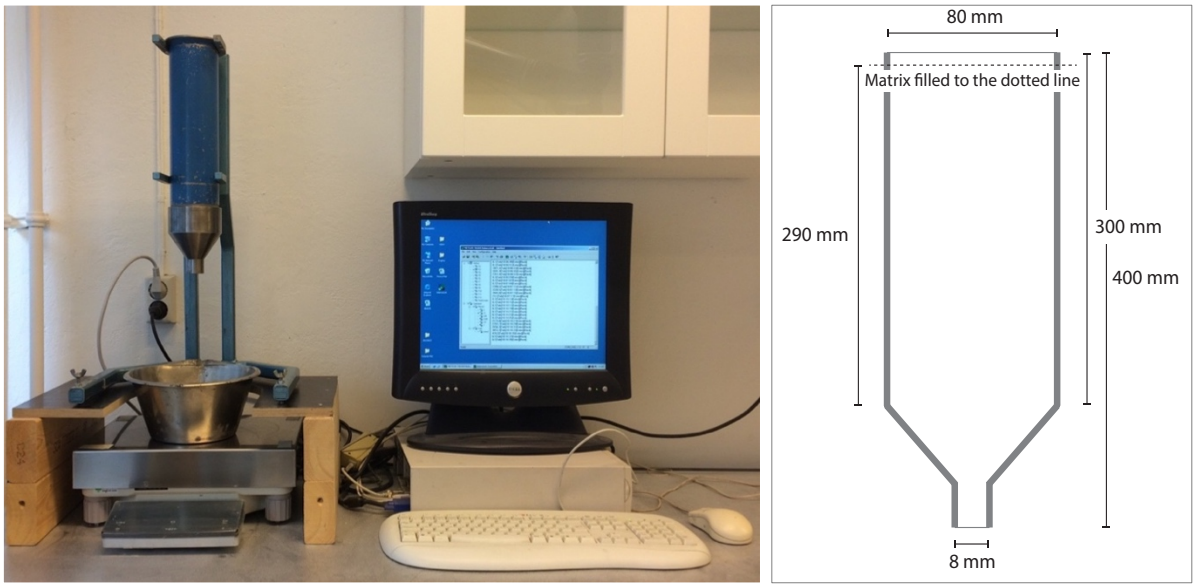


Figure 3.3: The experimental setup of the FlowCyl test - The apparatus includes a purpose-made cylindrical steel tube, a steel container, an electronic scale and a computer for recording (left). The dimensions of the cylindrical steel tube (right).

For each measurement, the prepared mix was poured into the steel tube until the tube was filled up to 10 mm below the top edge, whilst the outlet was closed by a finger. Thereafter, the data recording was started manually and the outlet opened. The accumulated increase of mass in the container, and thus the fluid flow, was measured and recorded continuously at a sample rate of 2 s until the steel tube was empty and the recording was stopped manually. The software Balance Link was used for the data recording.

In FlowCyl test serie I, each mix was examined visually right after the FlowCyl test. The examination included evaluation of the homogeneity and the stability properties of the mix.

3.3.3 Calculation of the flow resistance

The FlowCyl test gives the flow resistance of the tested mix. The flow resistance, λ_Q, is defined as the ratio between the average flow loss of the measured fluid, $\bar{Q}_t$, and the average theoretical fluid flow of the ideal fluid, $\bar{Q}_i$. The flow loss is simply the difference between the ideal fluid flow, Q_i, and the measured fluid flow, Q_h, which for practical reasons is simplified with an empirical 2nd polynomial shape function, Q_{tf}. Hence, the following equations apply:

$$\lambda_Q = \frac{\bar{Q}_t}{\bar{Q}_i} = \frac{(\int_{h_1}^{h_2} Q_{tf} \cdot dh)/(h_2 - h_1)}{(\int_{h_1}^{h_2} Q_i \cdot dh)/(h_2 - h_1)}$$

$$Q_t = Q_i - Q_h \approx Q_{tf}$$

where

λ_Q - flow resistance [-]
$\bar{Q}_t/Q_t$ - average- / flow loss of the measured fluid [m^3/s]
$\bar{Q}_i/Q_i$ - average- / fluid flow of the ideal fluid [m^3/s]
Q_h - fluid flow of the measured fluid [m^3/s]
Q_{tf} - empirical shape function determined from regression analysis [m^3/s]
h_1 - lower boundary of the fluid level in the steel tube (380 – 400 mm) [mm]
h_2 - upper boundary of the fluid level in the steel tube (125 – 150 mm) [mm]

Hence, the flow resistance is dimensionless and ranges from 0 for an ideal fluid to 1 as an upper limit for very viscous fluids. Some typical values are shown in Table 3.15.

Table 3.15: Typical values of the flow resistance for different materials. Extracted from [7].

Material	Flow resistance
Water	0.10
Matrix in M60 concrete (w/b = 0.60)	0.30 – 0.40
Matrix in M45 concrete (w/b = 0.45)	0.50 – 0.60
Matrix in SCC	0.45 – 0.75

For each measurement, the flow resistance was determined based on the recorded data. The calculation was performed in a purpose-made Excel spreadsheet. Recorded data and calculation of the flow resistance of one of the performed tests are given as a demonstration in Appendix A.5. The mathematical derivation of λ_Q can be found in [7] [18] [16].

3.3.4 Fresh concrete testing

Table 3.16 shows the properties that have been determined for each of the basic mixes presented in section 3.3, along with the associated documents where the procedure for determining these properties is described.

Table 3.16: The properties for which the basic mixes have been tested.

Property	Document	Requirement
Temperature	-	Min. 20 °C and max. 35 °C, unless lower/higher temperatures are agreed between user and producer [23].
Slump	NS-EN 12350-2 [51]	200 – 240 mm is normally required and expected by the user [19].
Slump-flow	NS-EN 12350-8 [52]	-
Rheology	4SCC operating manual	-
Stability	KL VSI (Appendix A.6)	A castable concrete requires a stability corresponding to $VSI^m \leq 0.5$ and $VSI^f \leq 0.6$. See Appendix A.6.
Density	NS-EN 12350-6 [53]	Should not deviate too much from the designed value.
Air content	NS-EN 12350-7 [54]	Should not deviate too much from the designed value.
28d-strength	NPRA's handbook R015	Min. 45 MPa for 100x100x100 mm cubes [23] [29].

3.3.4.1 Mix design

The mix design of the three main basic mixes and the fourth additional basic mix investigated in this study is presented in section 3.3.

3.3.4.2 Mixing procedure

A forced pan mixer with a volume of 50 litres from Eirich was used to prepare the basic mixes. The volume of each mix was 30 litres. The applied mixing procedure comprises the following steps:

- 1 minute dry mixing
- 2 minutes mixing whilst adding water and some superplasticizer during the first minute.
- 2 minutes resting
- 0.5 minutes mixing whilst adding superplasticizer until the concrete consistency correlates to a slump of 220 – 240 mm
- 1.5 minutes mixing

3.3.4.3 Temperature measurement

The temperature was measured for each basic mix right after mixing. A simple thermometer stick was used. Normally, the temperature of fresh concrete at delivery is restricted to specified limiting values since the hydration process is strongly influenced by temperature. NB7 [23] requires that the temperature of the basic mix at delivery lies between 20 °C and 35 °C, unless other temperatures are documented to be advisable for the current situation.

3.3.4.4 Slump test

The *slump test* is the most common method to measure or characterize the workability of fresh concrete used in ordinary concrete structures [7]. For sprayed concrete, the slump is commonly used as a quality parameter in production, that is, a desired slump is specified by the user for which the producer must ensure is fulfilled at delivery. Typical slump values for sprayed concrete lie in the range of 200 – 240 mm [19].

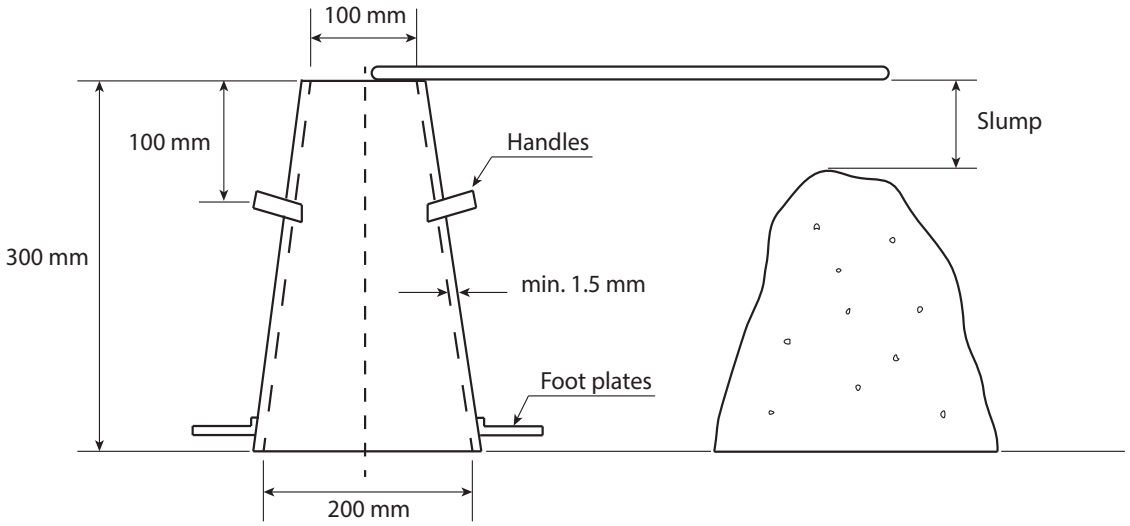


Figure 3.4: The standardized dimensions of the open-ended cone used for the slump test and the definition of slump according to NS-EN 12350-2 [51].

The slump test is described in NS-EN 12350-2 [51]. The apparatus used for the slump test consists of an open-ended steel cone with the dimensions shown in Figure 3.4, a steel rod with circular cross section and a baseplate with smooth surface. For each measurement, the cone and the baseplate were dampened with a moist cloth before the cone was placed on the baseplate and filled with fresh concrete in three layers. Each layer of approximately one-third of the total cone height was compacted by tamping with the rod 25 times. When the cone was entirely filled, the top was evened with the rod and excessive material was removed from the cone and the baseplate. Finally, the cone was lifted slowly and steadily in vertical direction. The slump was measured as the average height difference between the top of the cone and the top of the fresh concrete at rest, as shown in Figure 3.4.

3.3.4.5 Slump-flow test

The *slump-flow test* is a combination of the slump test and the so-called *flow table test*, and was originally developed to characterize the properties of SCC and is in fact mostly used for this type of concrete. The standard procedure for determining the slump-flow is described in NS-EN 12350-8 [52]. In this study, the slump-flow was measured simultaneously with the slump by measuring the diameter of the circularly shaped fresh concrete formed on the baseplate in two perpendicular directions and taking the mean value.

3.3.4.6 Rheometer test

Simultaneously with the slump test and the slump-flow test, the rheology of each basic mix was characterized by using a ConTec Rheometer-4SCC. The measurement setup is presented in Table 3.17 and the rheometer device is shown in Figure 3.5.

The torque, T, was measured as a function of the rotational speed, N. A sample rate of 1/4 s was chosen. Based on this function, the rheological parameters G and H[7] were determined from linear regression; G was determined as the point of intersection between the line and the ordinate and H as the slope of the line, both corrected for the inherent torque of the device, i.e. the torque measured with an empty container. This is shown in Appendix A.7. In theory, these parameters can be converted into the Bingham parameters; the yield stress, τ_o, and the plastic viscosity, μ. However, due to complicated geometry of the rotary vane of the rheometer, this conversion is currently not possible. Hence, only G and H will be determined and further discussed. Yield stress and plastic viscosity mean implicitly G and H when these terms are used in the following discussions.

Figure 3.5: ConTec Rheometer-4SCC apparatus. Extracted from [55].

Table 3.17: Measurement setup for ConTec Rheometer-4SCC.

Rotational speed [rps]	0.47	0.40	0.33	0.27	0.20	0.13	0.07
Duration [s]	10	5	5	5	5	5	5
Measurement points	40	20	20	20	20	20	20

[7] The parameters G and H are equivalent to the parameters g and h in section 2.1.2.

According to the operating manual of the device, the units of G and H are [A] and [As], respectively. Hence, the unit of T is [mA].

3.3.4.7 Stability assessment

The stability of each basic mix was assessed by means of the *Visual Separation Index* developed by Knut Lervik (KL VSI), which is presented in Appendix A.6. The index ranges from 0 (stable and homogenous) to 1 (complete separation). The KL VSI was determined based on visual examination of the basic mix in the mixer right after mixing, VSI^m, and on the flow board right after determination of the slump-flow, VSI^f. A castable concrete requires a VSI^m between 0 – 0.5 and a VSI^f between 0 – 0.6.

3.3.4.8 Determination of air content and density

The concrete density and the air content were determined for each basic mix after the slump- and the slump-flow test. The procedures are described in NS-EN 12350-6 [53] and NS-EN 12350-7 [54]. The apparatus includes a pressure gauge meter with a 5 litres steel container. Fresh concrete was transferred into the container until it was entirely filled, compacted with a steel rod and weighted. The density was simply determined from the weight and the volume of the sample inside the container. After weighting the sample, the air content was determined as described in the standard. The *gauge method* was applied. Both the density and the air content are involved in the mix design and thus the measured values should not deviate too much from the designed values.

3.3.4.9 Determination of compressive strength

Two 100x100x100 mm cubes were casted for each basic mix. The cubes and the mould were covered with plastic right after casting and stored in laboratory atmosphere for 24 h. Thereafter, the cubes were de-moulded and cured in water until testing, i.e. 28 d after casting. The procedure is described in NS-EN 12390-3 [56]. For compressive class B35, the compressive strength is required to be at least 45 MPa according to NS-EN 206 [29].

3.4 Experimental errors and uncertainties

The experimental errors and uncertainties are listed below:

- The Pyknometer method used to determine the water absorption is less suitable for crushed sand, especially crushed sand with a high content of fines and flaky and elongated particles. This will be further discussed in chapter 4.
- The procedure for homogenizing the combined sand materials in the void content test was simplified by using a tall bucket with lid. The homogenizing was carried out by rolling the bucket on its long side with the combined sand material inside for several minutes.
- The flow resistance values determined in the FlowCyl test series I and II were all based on one single measurement due to lack of capacity and materials.
- The predetermined superplasticizer dosage for each mix in the FlowCyl test series I and II was weighed and stored in a small plastic container. The uncertainty related to the amount of superplasticizer added into each mix was attempted minimized by correcting for the amount left in the container. The weight of each container was weighted before and after the FlowCyl test with an electronic precision balance with 0.001 g readability. Hence, the final content of superplasticizer in each mix is not exactly the same as the designed content.
- The rotational speed of the drill mixer used in the FlowCyl test series I and II was lowered at low battery. The variation in shear rate exerted on the different mixes was attempted minimized by changing and recharging the battery for every second mix. Unfortunately, in two of the mixes, the drill ran out of battery and the battery was changed during the mixing sequence.

4 RESULTS AND DISCUSSION

4.1 Results of the characterization of aggregates

The results of the characterization of aggregates are presented in Figure 4.1 and Table 4.1. Figure 4.1 shows the grading curves of the investigated sand materials. The grading in the particle size range 0.063 – 16 mm was characterized for all five sand materials, whereas the grading in the particle size range 0 – 0.125 mm was only characterized for MR1, MF and MU1. Table 4.1 shows the other characterized properties of the studied sand materials.

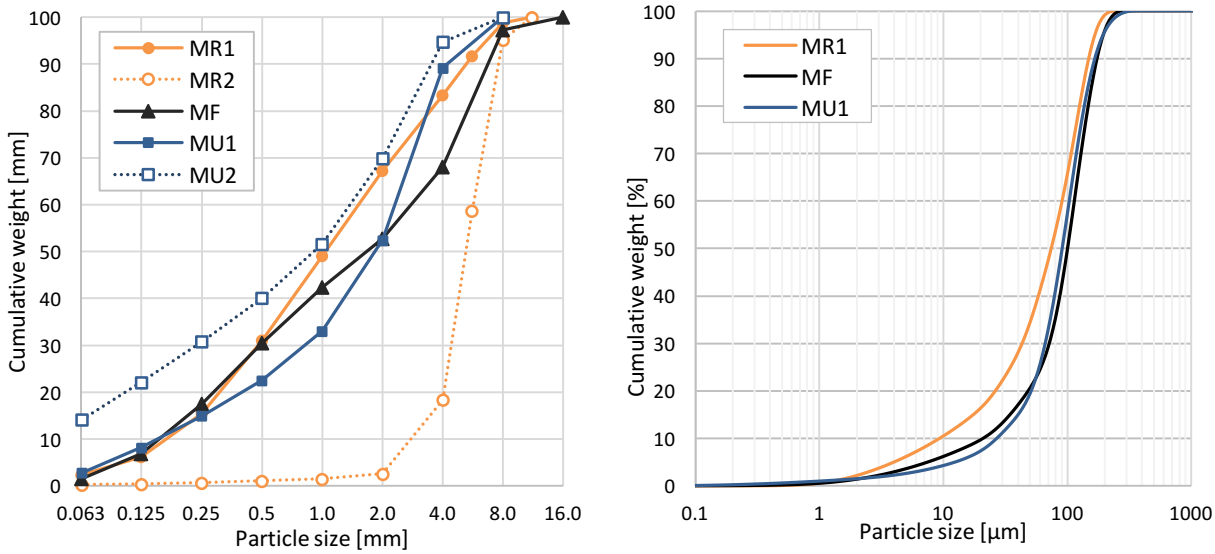


Figure 4.1: The grading curves of all five sand materials in the particle size range 0.063 – 16 mm determined by mechanical sieve analysis (left) and the grading curves of MU1, MF and MR1 in the particle size range 0 – 0.125 mm determined by Coulter analysis (right).

Table 4.1: The characterized properties of the sand materials.

	MR1 (reference)	**MR2**	**MF**	**MU1**	**MU2[d)]**
Fines[a)] content	3.0 %	0.5 %	1.5 %	2.7 %	14.0 %
Particle density	2.68 Mg/m^3	2.67 Mg/m^3	2.76 Mg/m^3	2.96 Mg/m^3	(2.96 Mg/m^3)
Water absorption	0.3 %	0.5 %	0.2 %	0.1 %	(0.1 %)
Content of flaky and elongated particles[b)]	25 % 20 %	-	40 % 25 %	70 % 55 %	(70 %) (55 %)
Free mica content	4 %	-	24 %	11 %	(11 %)
Specific (BET) surface area of fines[c)]	1.57 m^2/g	-	0.59 m^2/g	0.44 m^2/g	-

[a)] Fines = particles ≤ 0.063 mm.
[b)] The first value is related to the 2 – 4 mm fraction, whereas the second value is related to the 4 – 8 mm fraction.
[c)] Fines = particles ≤ 0.125 mm.
[d)] Only the fines content was characterized for MU2. The other properties were assumed to be approximately the same as those of MU1.

All the characterized geometrical properties, except for the grading, are compared with the specific surface area of fines for MR1, MF and MU1 in Figure 4.2.

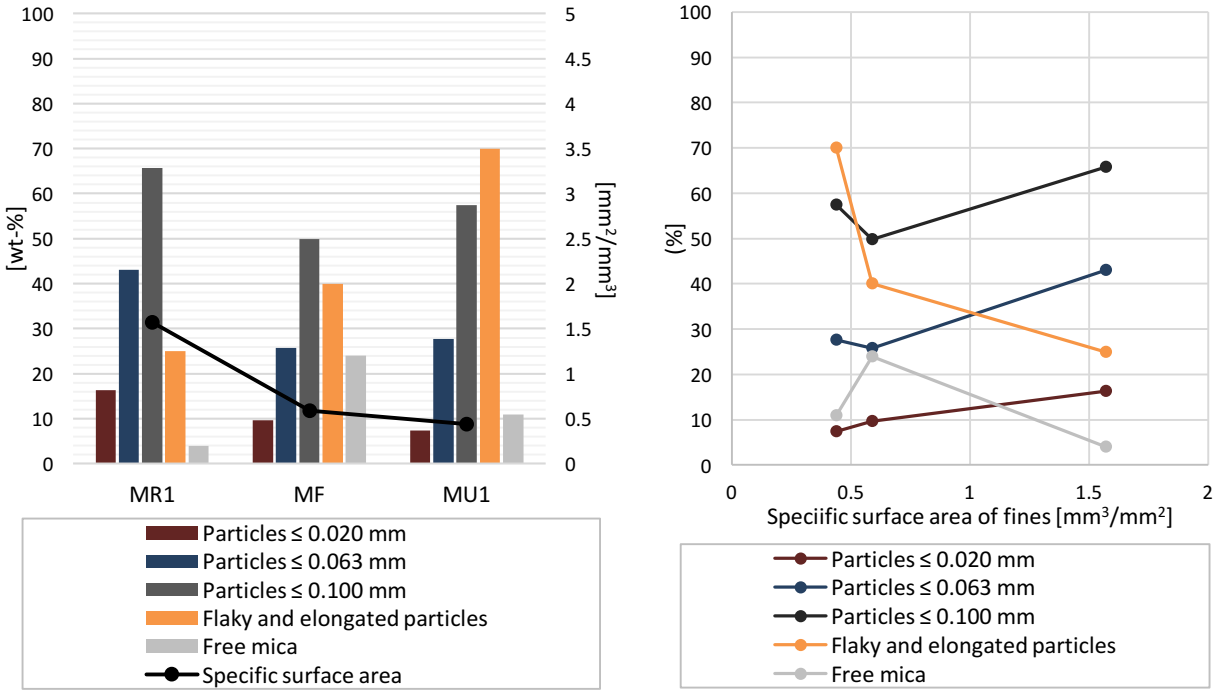


Figure 4.2: Comparison of the content of fine particles (≤ 20 µm, ≤ 63 µm and ≤ 100µm), irregularly shaped particles and free mica with the specific surface area of fines (particles ≤ 0.125 mm) by column chart (left) and line chart (right).

4.1.1 Grading

The grading of the studied sand materials is shown in Figure 4.1 (left). Except for the grading curves of MR2 and MU2, there are no significant differences between the grading curves that are worth mentioning here. As MU2 is unwashed it is reasonable that this material has the finest grading and the highest content of fine particles.

4.1.2 Fines content

The fines content of the investigated sand materials is presented in Table 4.1. As addressed in section 2.2.3, crushed aggregates tend to have a higher fines content than natural aggregates as great amounts of fine particles are generated during the crushing process. It is apparent from the fines content of the crushed sand materials that washing has been crucial to keep their fines content at an acceptable level. MU2 has a fines content of 14.0 %, whereas MU1 has a fines content of 2.7 %, which implies a difference of more than 10 %. These materials have demonstrated that the fines content of crushed sand can be significantly reduced and even get lower than the fines content of natural sand by including a wet classification step in the crushing process. However, classification of fines in general needs to be limited to some extent as a certain amount of fines is beneficial for the stability properties of concrete (see section 2.2.2.3). Except for MU2, all the studied sand materials seem to have a fines content within acceptable range with respect to both NPRA's requirements (max. 1.5 % for coarse aggregates and max. 10 % for natural graded aggregates) and concrete stability.

4.1.3 Particle density and water absorption

The particle density and the water absorption of the studied sand materials are presented in Table 4.1. The particle density of all sand materials lies in the typical range for Norwegian aggregates (see section 3.2.3). As all sand materials are composed of similar rock types, it is reasonable that the difference in particle density among these materials is small. Furthermore, all sand materials have a relatively low water absorption and satisfy NPRA's requirement of a value not higher than 1.5 %. In fact, the crushed sand materials have abnormal low values. This is possibly because the Pyknometer method used to determine the water absorption (see section 3.2.3) is less suitable for crushed sand. The definition of the surface dry state according to this method is less accurate for crushed sand, as the typical properties of crushed sand, i.e. the high content of fines and the non-equidimensional particles, contribute to increase the stability of the cone that is used to evaluate the moisture condition in the sand. Hence, it is more difficult to make the cone collapse when dealing with crushed sand, which results in lower water absorption values. Despite the limitations of the existing method, a method specifically designed for crushed sand has not been developed yet.

4.1.4 Content of flaky and elongated particles

The content of flaky and elongated particles of the studied sand materials is presented in Table 4.1. As expected, the crushed sand materials have a higher content of non-equidimensional particles than the reference material. As MU1 and MU2 are the least processed crushed sand materials, it is reasonable that these materials have the poorest particle shape quality. The improved particle shape quality of MF is likely attributed to the implementation of VSI in the crushing process. For all the investigated sand materials, the content of flaky and elongated particles in the 2 – 4 mm fraction is higher than in the 4 – 8 mm fraction. This has something to do with how the particles are processed in the crushers. As it is harder to exert forces on every single particle in the fine fraction than in the coarse fraction, it is more difficult to produce fine particles with beneficial shapes [57].

4.1.5 Free mica content

The free mica content of the investigated sand materials is presented in Table 4.1. The free mica content in MF exceeds NPRA's upper limit of 20 %. The content is considered as high. The free mica content in MU1 and MU2 meets NPRA's requirement and is considered as moderate. The relatively high content of free mica in the crushed sand materials can be attributed to the high production of fine particles in the crushing process, which includes free mica minerals when the rock materials contain mica. The production of fine particles is especially high when VSI is implemented (see section 2.2.3.1), which may explain why MF has the highest content of free mica. Washing may contribute to reduce the free mica content, but in order to remove mica minerals effectively, more advanced technology (e.g. froth floatation technique) must be applied. The relatively low content of free mica in the reference material indicates that this sand is produced from rock materials with low mica content.

4.1.6 Specific surface area of fines

The specific surface area of the fines of MR1, MF and MU1 is shown in Table 4.1 and Figure 4.2. In Figure 4.2, the different contents of fine particles (≤ 20 µm, ≤ 63 µm and ≤ 100 µm) are with respect to the 0 – 0.125 mm fraction and are extracted from the grading curves in Figure 4.1 (right). The content of flaky and elongated particles is related to the 2 – 4 mm fraction, whereas the content of free mica is related to particles in the particle size range 0.125 – 0.250 mm.

As addressed in section 2.2.2.1, the specific surface area of aggregates is strongly influenced by the geometrical properties of aggregates, including the grading, the fines content, the particle shape and the free mica content. It can be seen from Figure 4.2 that the specific surface area is strongly correlated to the content of fine particles in general. The correlation is most apparent for particles ≤ 20 μm. Hence, the studied sand materials have demonstrated that the specific surface area of fines is strongly governed by the content of the finest particles, especially particles ≤ approximately 20 μm, which is consistent with earlier findings [1] [18]. As can be seen from Figure 4.1 (right), the finer the grading the higher the specific surface area.

On the other hand, Figure 4.2 shows no direct correlation (or an unexpected correlation) between the specific surface area and the content of irregularly shaped particles and the free mica content, respectively. This can be explained by the fact that these parameters are related to different fractions.

4.2 Results of particle phase testing

The void content of the different aggregate compositions (see Table 3.9 in section 3.3.1.1) is shown in Figure 4.3. The void content of the aggregate compositions used in the investigated basic mixes is highlighted. The Excel spreadsheet used to calculate the void content for each aggregate composition is presented in the second part of Appendix A.3. Table 4.2 shows the necessary matrix volume to fill all voids and the matrix surplus related to the studied basic mixes. These values have been determined based on the measured void content values and the designed matrix volume of 430 l/m^3.

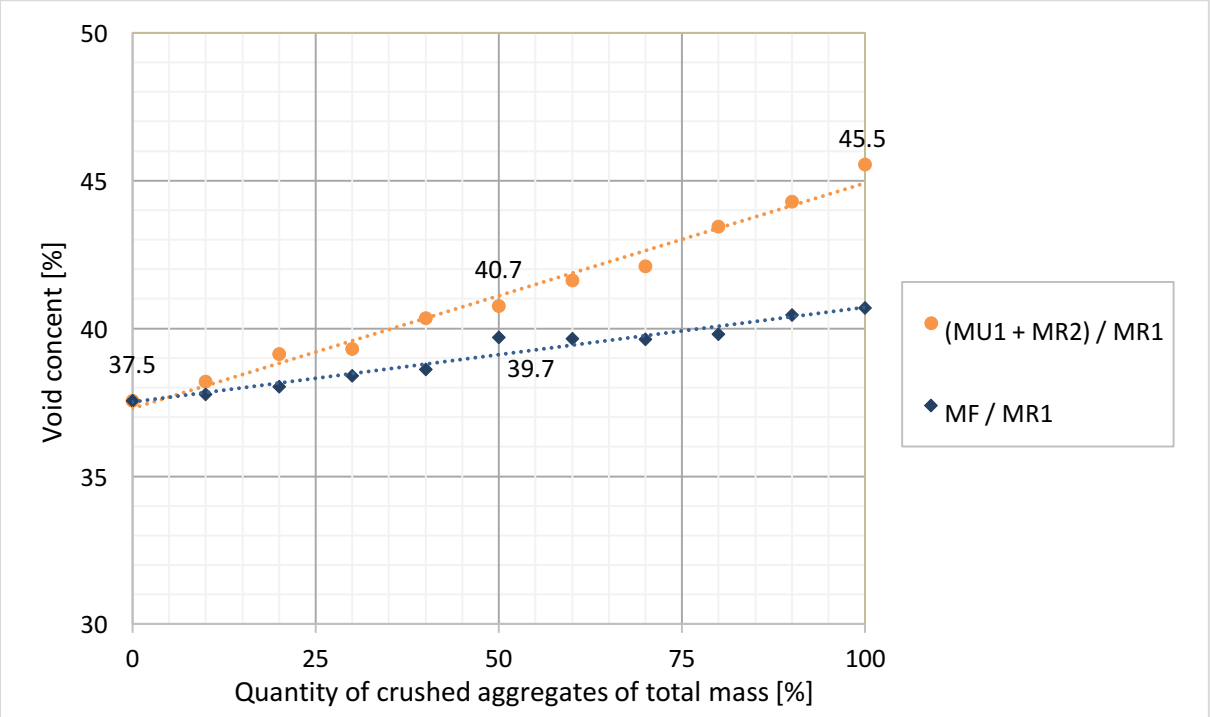


Figure 4.3: The measured void content values.

Table 4.2: The measured void content, the calculated matrix volume needed to fill all voids and the calculated matrix surplus related to the different basic mixes.

	Measured void content in particle phase [%]	**Matrix volume needed to fill all voids [l/m^3]**	**Matrix surplus of designed mix [l/m^3]**
Mix MR100	37.5	375	55
Mix MF50	39.5	395	35
Mix MU50	40.7	407	23
Mix MU100	45.5	455	- 25

Figure 4.3 shows that the crushed sand materials have a higher void content than the reference material. Among these materials, MU1 has the poorest particle shape quality and consequently the highest void content. The void content test is commonly performed to find the optimal aggregate composition, i.e. the aggregate composition with the lowest void content, in order to minimize the necessary matrix volume to achieve a certain workability. As the combined sand

materials in this study are all in the same fraction, there is no optimal way for the particles to pack together as for the case when coarse- and sand aggregates are combined. It is therefore logical that the void content increases linearly with the proportion of crushed aggregates, as shown with the dotted lines in Figure 4.3.

Experiences imply that a matrix surplus of 50 – 80 l/m^3 is needed to obtain a slump of 200 mm [7]. Hence, the matrix surplus of the investigated basic mixes shown in Table 4.2 is not very high. In fact, the matrix surplus of mix MU100 is negative, implying that the matrix volume is inadequate to fill all the voids.

Based on the values presented in Table 4.2, there is reason to believe that the three main basic mixes MR100, MF50 and MU50 are matrix dominated in which the fresh concrete properties are mainly governed by the properties of the matrix phase, whereas the fourth basic mix MU100 is particle dominated in which the properties of the particle phase play a more important role. This hypothesis will be used to interpret the results of the fresh concrete testing.

4.3 Results of the matrix phase testing

In the FlowCyl test series I, the effect of superplasticizer on the fluid properties of three matrix materials, equivalent to the matrix phase of the three main basic mixes, was studied by varying the dosage of superplasticizer. The results are presented in Figure 4.4, Table 4.3 and Figure 4.5. (H) and (D) stand for the Hobart mixing method and the drill mixing method, respectively. In this test series, all the mixes with a superplasticizer content of 0.5 % by binder weight were too viscous to be measured and evaluated and will not be discussed here.

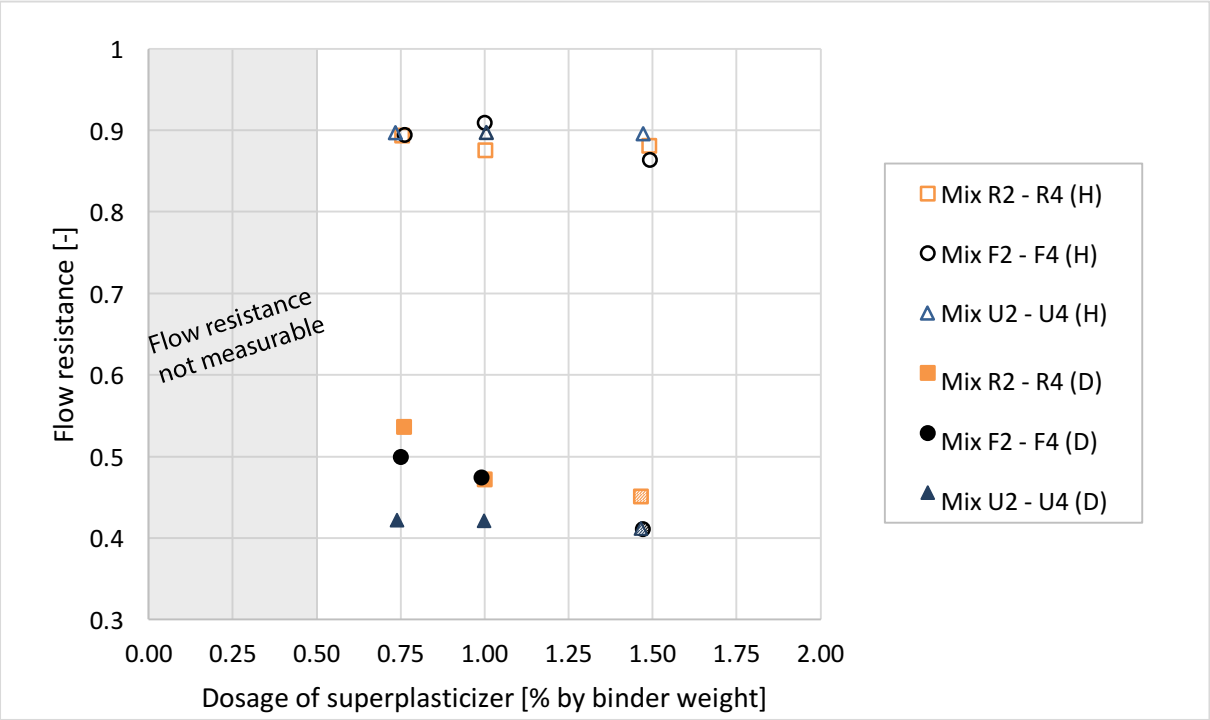


Figure 4.4: The flow resistance of the studied matrix materials for different dosages of SP. Partly filled markers imply that signs of separation were observed.

Table 4.3: Results of the visual assessment of the different mixes.

Mix	SP	I	S	Mix	SP	I	S
$R1_I$ (H)	0.50	-	-	$R1_I$ (D)	0.50	-	-
$R2_I$ (H)	0.75	X		$R2_I$ (D)	0.75		
$R3_I$ (H)	1.0	X		$R3_I$ (D)	1.0		
$R4_I$ (H)	1.5	X		$R4_I$ (D)	1.5		(X)
$F1_I$ (H)	0.50	-	-	$F1_I$ (D)	0.50	-	-
$F2_I$ (H)	0.75			$F2_I$ (D)	0.75		
$F3_I$ (H)	1.0			$F3_I$ (D)	1.0		
$F4_I$ (H)	1.5	X		$F4_I$ (D)	1.5		(X)
$U1_I$ (H)	0.50	-	-	$U1_I$ (D)	0.50	-	-
$U2_I$ (H)	0.75			$U2_I$ (D)	0.75		
$U3_I$ (H)	1.0			$U3_I$ (D)	1.0		
$U4_I$ (H)	1.5	X		$U4_I$ (D)	1.5		(X)

I	Inhomogeneity	X	Present
S	Separation	(X)	Slightly present
SP	Dosage of SP in wt-% of binder content	-	FlowCyl test failed. Visual examination omitted.

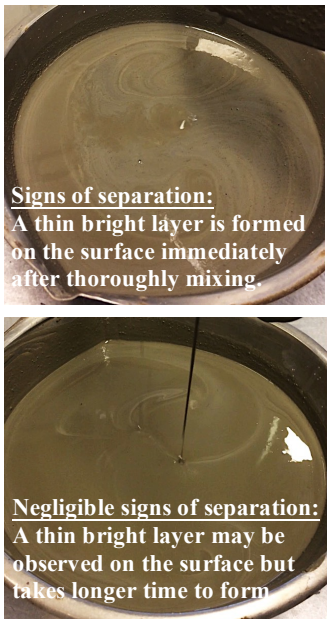


Figure 4.5: Visual assessment of matrix stability.

In the FlowCyl test series II, the effect of specific surface area on the fluid properties of three matrix materials composed of different fines was studied by varying the fines/binder ratio (f/b ratio). The results are presented in Figure 4.6. The f/b ratio in % related to the different mixes and the equation of the established trend lines are shown in the figure.

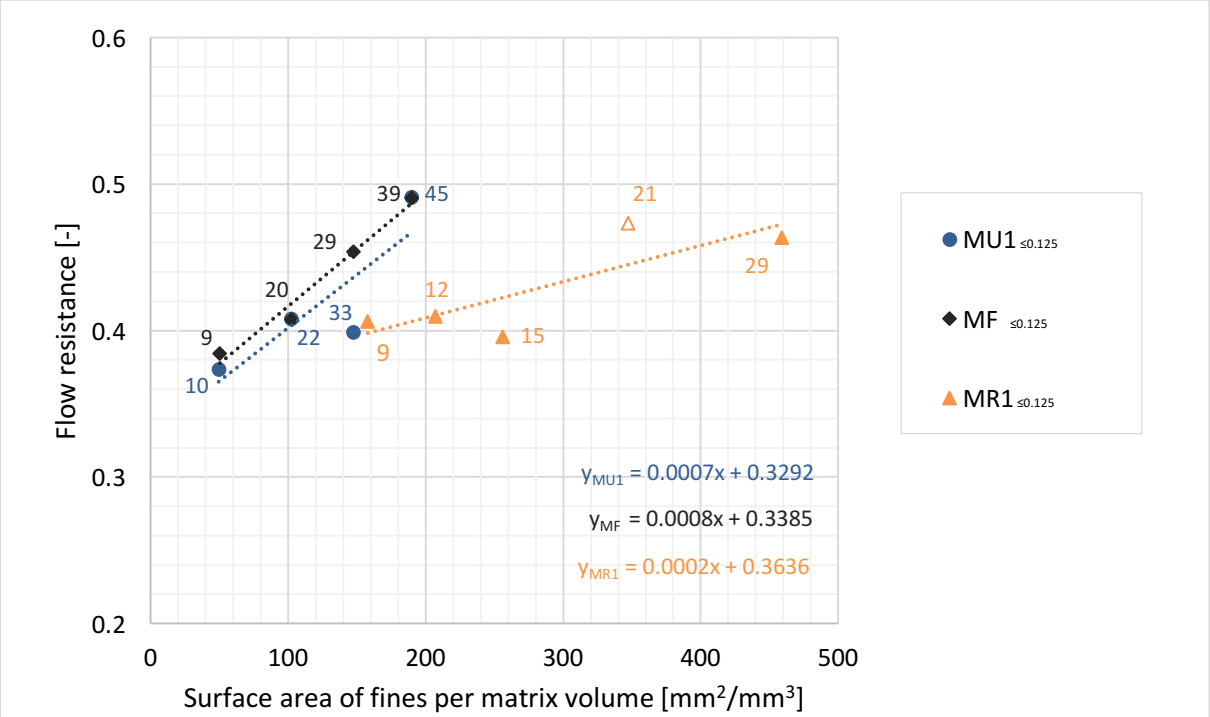


Figure 4.6: The relationship between flow resistance and surface area of fines (particles ≤ 0.125 mm). The marker without fill is taken from the FlowCyl test series I (mix $R3_I(D)$).

4.3.1 Results of the FlowCyl test series I

It is evident from Figure 4.4 that the Hobart mixing method produces mixes with much higher flow resistance values than the newly developed drill mixing method. This observation is likely related to the difference in shear rate generated during mixing. Ng et al. [47] showed in their study that the rheological properties of matrix materials are strongly influenced by the shear rate to which they are subjected. Hence, significant difference in flow resistance can be observed for the same matrix material due to different choice of preparation procedure.

In general, the Hobart mixer generates a lower shear rate than the handheld drill mixer (see Table 3.12 in section 3.3.2.2), which explains its reduced dispersing ability. Inhomogeneity in terms of lumps and agglomerates were observed in most of the mixes prepared with the Hobart mixer, as shown in Table 4.3. Furthermore, the mixes prepared with the Hobart mixer show less variation both with respect to one another and with respect to the dosage of superplasticizer, which indicate a reduced effect of the superplasticizer due to inadequate dispersion. The total effect of the Hobart mixer's reduced dispersing ability is increased flow resistance values and the absence of a decreasing trend of the flow resistance with increasing dosage of superplasticizer.

The mixes prepared with the drill mixing method, on the other hand, show better properties in terms of homogeneity and have more realistic flow resistance values (see Table 3.15 in section 3.3.2.3). However, these mixes seem to have a higher risk of separation. Among these mixes, those with 1.5 % superplasticizer by cement weight showed signs of separation, in the sense

that a thin, bright layer on the surface was quickly formed after thoroughly mixing with a spatula, as shown in Figure 4.5. It is likely that this film observed on the surface is bleeding water, which is typical for fluid concrete mixes with high water content and/or high dosage of superplasticizer. The apparent decrease in flow resistance with increasing dosage of superplasticizer indicate that the superplasticizer is more efficient.

4.3.2 Results of the FlowCyl test series II

The linear relationship between the surface area of fines and the matrix flow resistance, which already has been demonstrated in several studies including [1] and [22], is apparent for all three types of fines as shown in Figure 4.6. These fines will be further denoted as $MR1_{\leq 0.125}$, $MF_{\leq 0.125}$ and $MU1_{\leq 0.125}$. The specific surface area of these fines, which is presented in Table 4.1, has been used to estimate the total surface area of fines in each mix. Note that the method using grading to determine the specific surface area of fines was applied in [1] and [22], whereas the BET-analysis was applied in the current study (see section 3.2.6). The values on the primary axis in Figure 4.6 is therefore much higher than those found in [1] and [22].

It is apparent from Figure 4.6 that the trend line associated to the mixes containing $MR1_{\leq 0.125}$ has the smallest slope, indicating that the flow resistance of these mixes is least sensitive to changes in surface area of fines, which in practice are caused by changes in fines content or fines grading. Hence, based on Figure 4.6, there is reason to believe that $MR1_{\leq 0.125}$ possess a better performance, in terms of lower flow resistance, in the matrix phase than $MF_{\leq 0.125}$ and $MU1_{\leq 0.125}$.

However, for fines with different specific surface area, the same relative change in fines content or fines grading will not give the same relative change in surface area. Figure 4.6 shows that an increase in f/b ratio from around 10 % to around 20 % gives a relative increase in surface area of around 200 mm^2 for $MR1_{\leq 0.125}$, but only around 50 mm^2 for $MU1_{\leq 0.125}$ and $MF_{\leq 0.125}$. In fact, for a given f/b ratio, $MR1_{\leq 0.125}$ seems to give higher flow resistance values than $MU1_{\leq 0.125}$ and $MF_{\leq 0.125}$. This observation is in agreement with the results in Figure 4.4. Note that the values in Figure 4.4 are based on matrix compositions with a f/b ratio around 20 % and where the crushed fines are combined with natural fines. One can expect somewhat greater differences for mixes containing unmixed fines than for those shown in Figure 4.4.

Hence, for mixes that contain fines with different specific surface area, their sensitivity to variation in surface area, caused by for example variation in f/b ratio, will not necessary correlate with their performance with respect to the flow resistance. Despite that $MR1_{\leq 0.125}$ provides mixes that are least sensitive to changes in surface area, this material gives mixes with the highest flow resistance values due to its high specific surface area, as shown in Table 4.1.

4.4 Results of the fresh concrete testing

The results of the fresh concrete testing are summarized in Table 4.4. The geometrical properties of the (combined) aggregates used in the basic mixes are presented in Table 4.5 and Figure 4.7. The grading curves in Figure 4.7 have been extracted directly from the Excel spreadsheet used for the proportioning of the basic mixes (see Appendix A.2), whereas the fines content, the content of flaky and elongated particles and the free mica content in Table 4.5 have been calculated from the results of the characterization of aggregates (see Table 4.1).

Table 4.4: The results of the fresh concrete testing.

Mix[a)]	Temp [°C]	Density [kg/m^3]	Air content [%]	SP dosage [%][b)]	Stability[c)]	Slump [mm]	Slump - flow [mm]	Rheology parameters G[A]	Rheology parameters H[As]	Comp strength [MPa]
MR100	22	2210	6.4	0.62	0 – 0.1	225	410	1929	1312	65.9
$MF50_1$	-	-	-	0.58	-	160	-	-	-	-
$MF50_2$	22	2209	7.7	0.72	0 – 0.1	230	390	2156	1988	63.2
MU50	22	2243	7.5	0.63	0 – 0.1	220	380	2502	1765	68.0
$MU100_1$	-	-	-	0.73	-	195	-	-	-	-
$MU100_2$	22	2320	8.0	0.80	0 – 0.1	215	360	2650	4485	71.3

[a)] Mix MF50 and mix MU100 were mixed in two sequences as the first dosage of superplasticizer gave too low slump value and more superplasticizer and further mixing were necessary.
[b)] Dosage of superplasticizer is given in percentage of total binder content.
[c)] Stability evaluation based on KL VSI, which can be found in Appendix A.6. The given values apply to the concrete mix both right after mixing (VSI^m) and right after slump-flow measurement (VSI^f).

Table 4.5: The content of fines, flaky/elongated particles and free mica in the studied basic mixes.

	Fines content [%]	Content of flaky/elong. particles [%][a)]	Mica content [%]
MR100	3.0	25 20	4
MF50	2.3	33 23	14
MU50	2.7	48 35	8
MU100	2.7	70 55	11

[a)] The upper value is related to the 2 – 4 mm fraction, whereas the lower value is related to the 4 – 8 mm fraction.

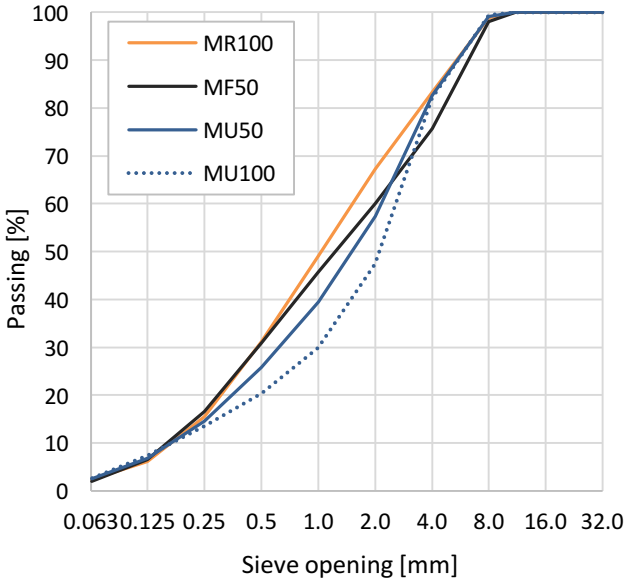


Figure 4.7: The grading curves of the (combined) aggregates used in the basic mixes.

Some of the values in Table 4.4 and Table 4.5 are compared graphically in Figure 4.8 and Figure 4.9. The following discussions are mainly based on these figures.

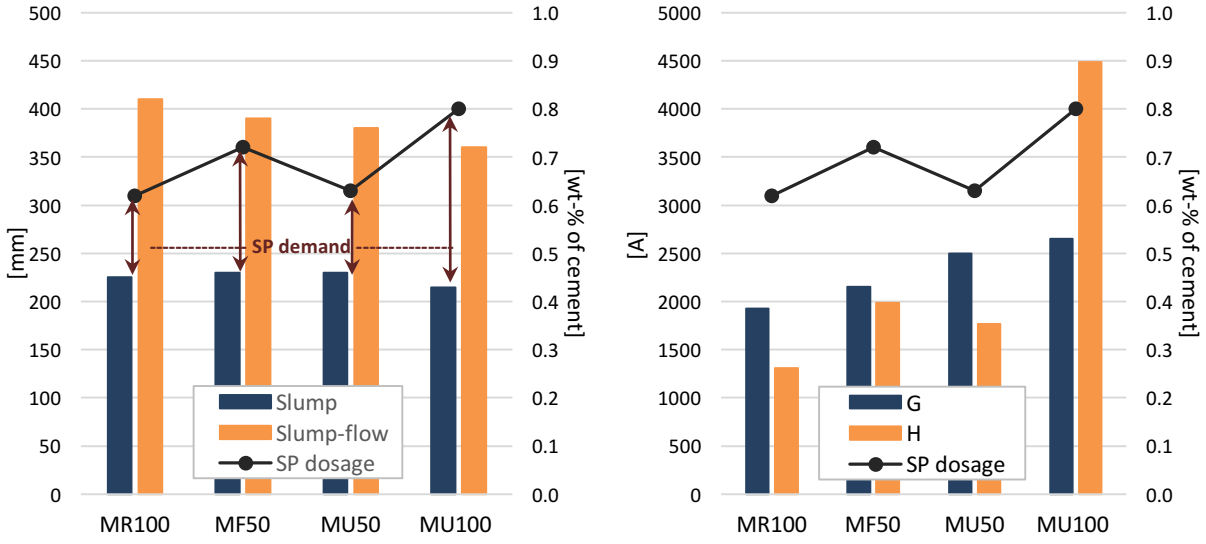


Figure 4.8: Slump, slump-flow and SP dosage for the different basic mixes (left). G, H and SP dosage for the different basic mixes (right).

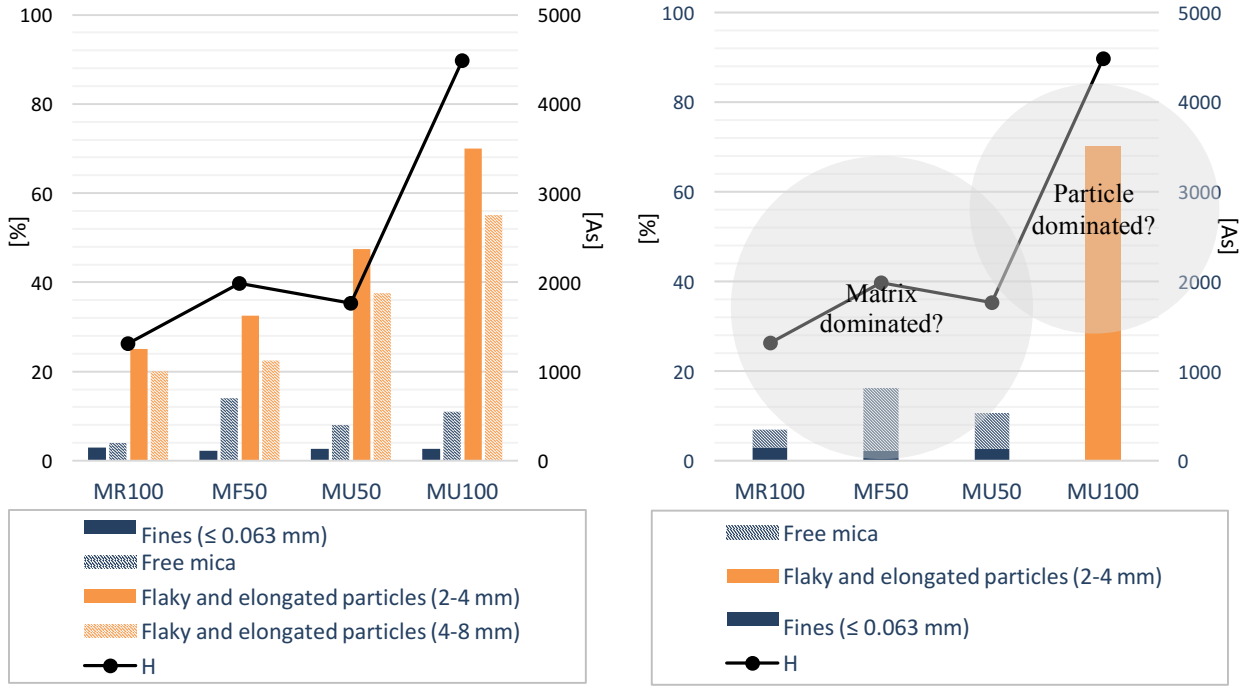


Figure 4.9: Comparison between the geometrical properties (fines content, content of flaky and elongated particles and free mica content) and H for all four basic mixes (left). Comparison between the fines content + the free mica content and H for MR100, MF50 and MU50 and comparison between the content of flaky and elongated particles and H for MU100 (right).

4.4.1 Density and air content

The density and the air content of the studied basic mixes are shown in Table 4.4. These properties were determined to check if the produced mixes are comparable with the designed mixes and to evaluate whether new mixes should be carried out or not.

For all four basic mixes, the measured air content is higher than the designed value and the measured density is correspondingly lower. The measured densities differed from the designed values by 2.4 % – 3.9 %, which can be considered as within acceptable variation. The measured air contents, on the other hand, are more than doubled compared to the designed values (3 % for all four mixes) and might therefore have influenced the fresh concrete properties. A high amount of air will contribute to increase the matrix volume[8] and may therefore have an effect on the concrete rheology [7]. However, as the basic mixes have similarly high air content, one can expect comparable results and the possible effect of excessive air content will not be further discussed here.

All four basic mixes have a quite high natural air content considering that the content normally lies in the range 2 – 3 % [7]. The high content of air can be related to the high content of fine aggregates in the mixes, as only aggregates in the 0 – 8 mm fraction have been used.

4.4.2 Stability and superplasticizer dosage

The results of the stability visual assessment and the content of superplasticizer of the investigated basic mixes are shown in Table 4.4. The stability of the fresh concrete both in the concrete mixer (VSI^m) and on the flow board (VSI^f) was characterized as stable and homogenous (0 – 0.1) for all four basic mixes. Furthermore, the applied dosage of superplasticizer can be considered as normal for all four basic mixes.

The superplasticizer demand of each mix is illustrated in
Figure 4.8 (left). As expected, mix MU100 has the highest superplasticizer demand. What is less expected, is that the other three mixes have quite similar superplasticizer demand and that mix MU50 is comparable with mix MR100, which respectively have the worst and the best aggregate quality in terms of particle shape among these three mixes. A possible explanation to these observations is the previously established hypothesis that the main basic mixes MR100, MF50 and MU50 are matrix dominated and mix MU100 is particle dominated (see section 4.2). The small variation in superplasticizer demand among the mixes MR100, MF50 and MU5 can be related to the rather small variation in the fluid properties of their matrix phases (see Figure 4.4 in section 4.3), whereas the higher superplasticizer demand of mix MU100 can be ascribed to the rather high content of flaky and elongated particles in its particle phase, i.e. the sand material MU1 (see Table 4.1 in section 4.1).

It is important to stress the fact that the superplasticizer demand of mix MU100 is rather low compared to what the aggregate quality indicates and was expected to be much higher. This fact may seem to contradict the hypothesis that mix MU100 is particle dominated and that its properties are predominantly governed by the properties of the particle phase. However, it is important to keep in mind that superplasticizer only affects the slump by altering the flow resistance of the matrix phase. The superplasticizer demand of mix MU100 is higher than the other three mixes because the high content of flaky and elongated particles (high interparticle friction and limited relative motions between particles) must be compensated with a lower flow

[8] The air content is not included in the PM model according to the definition, but can be considered as a part of the matrix phase in practice [7].

resistance of the matrix phase in order to obtain a given slump. As the sand material MU1 has proven to give the lowest flow resistance values due to its low specific surface area (see section 4.3), one can expect that only a small increase in superplasticizer content is necessary for mix MU100 to compensate for its low aggregate quality.

4.4.3 Slump, slump-flow and *G*

The measured values of the slump and the slump-flow are presented in Table 4.4 and illustrated in Figure 4.8 (left). As the superplasticizer content in each basic mix has been adjusted to ensure a slump of 220 – 240 mm, the measured slump values are approximately the same. The measured slump-flow values, on the other hand, seem to vary slightly.

It has been proven by several authors, including Morinaga [58], Wallevik [59] and Laskar [60], that the slump and the slump-flow are inversely correlated to the yield stress. The inverse correlation between the slump-flow and the yield stress can be observed in the present results. Figure 4.8 (left) shows that there is a slight decrease in slump-flow from mix MR100 with the highest particle shape quality to mix MU100 with the poorest particle shape quality, that is, with increasing content of flaky and elongated particles. Furthermore, Figure 4.8 (right) shows that there is correspondingly a slight increase in *G,* which is equivalent to the yield stress, with increasing content of flaky and elongated particles. These observations can be explained by the fact that the particle shape quality of aggregates has an influence on the interparticle friction, in the sense that flaky and elongated particles tend to increase the frictional forces between the aggregate particles and thus the yield stress of the concrete. Increased yield stress means that a higher shear stress (caused by gravitational forces) must be exerted on the concrete before it starts to flow and that a lower slump-flow value is achieved. Hence, the higher the content of flaky and elongated particles, the higher the parameter *G* and the lower the slump-flow.

The correlation between the slump and the yield stress is however absent (or less apparent) in the present results. A possible explanation is that the slump test is less suitable for characterizing the rheological properties of the studied basic mixes compared to the slump-flow test, as the mixes are relatively flowable. According to NS-EN 12350-2 [51], alternative tests should be carried out if the studied concrete mix has a slump greater than 210 mm.

4.4.4 Geometrical properties of aggregates and *H*

The measured *H* values are presented in Table 4.4 and are compared with the associated superplasticizer contents in Figure 4.8 (right) and the associated geometrical properties (except for the grading) in Figure 4.9. The grading is not included in the following discussion because this property is, in fact, taken into account in the fines content and the void content of the particle phase.

It is evident from Figure 4.8 (right) that H is strongly influenced by the aggregate properties. This parameter is comparable with the plastic viscosity (see section 3.3.4.6), which in turn is a measure of the mobility of concrete [7]. It was addressed in section 2.1.1 that the flowability of fresh concrete is restricted by interparticle friction, cohesion and viscosity. Hence, according to the PM model, the mobility of a matrix dominated mix is primarily governed by the flow resistance of the matrix phase, whereas the mobility of a particle dominated mix is mainly influenced by the interparticle friction and the relative motions between particles in the particle phase.

Based on the results of the void content test (see Table 4.2 in section 4.2), there is reason to believe that the main basic mixes MR100, MF50 and MU50 are matrix dominated, whereas the fourth basic mix MU100 is particle dominated. One can therefore expect that the fresh concrete properties of the mixes MR100, MF50 and MU50 are predominantly governed by the

properties of their matrix phases, whereas the workability of mix MU100 is mostly influenced by the properties of its particle phase. Hence, in order to explain the variation of the measured *H* values, it is reasonable to start checking if there are any correlations between *H* and the parameters governing the properties of the two phases, i.e. the geometrical properties of the sand materials (see Figure 2.8 in section 2.2.2). This is done in Figure 4.9.

It is hard to tell if there are any direct correlations between *H* and the geometrical properties when these parameters are presented all together as shown in Figure 4.9 (left). However, a strong correlation is revealed when these parameters are organized into a matrix dominated part and a particle dominated part as shown in Figure 4.9 (right). The *H* values of the matrix dominated mixes MR100, MF50 and MU50 are compared with the geometrical properties that primarily govern the flow resistance of the matrix phase; in this case the fines content and the free mica content. *H* of the particle dominated mix MU100 is compared with the geometrical properties that mainly govern the interparticle friction and the relative motions between particles in the particle phase; in this case the particle shape quality. As the content of flaky and elongated particles is associated to the 2 – 4 mm fraction, it is found reasonable to relate this property to the particle phase.

As mentioned in section 2.2.2, the fines content and the free mica content have an impact on the fluid properties of the matrix phase, as a high content of these constituents contributes to increase the specific surface area of fines and thus the flow resistance of the matrix phase. For matrix dominated mixes, large amounts of fine particles and mica minerals will therefore affect the workability properties negatively in terms of lower mobility. This relationship can be observed in the present results in Figure 4.9 (right), where the workability properties of the matrix dominated mixes, characterized by the plastic viscosity (*H*), are positively correlated to the total content of fines and free mica. The higher the content, the higher the plastic viscosity. In section 4.1, no direct correlation between the specific surface area of fines and the free mica content was detected. However, the positive correlation between the plastic viscosity and the free mica content may have revealed a possible correlation between these parameters, provided that the assumption that the mixes are matrix dominated is true, i.e. that the plastic viscosity is primarily governed by the flow resistance of the matrix phase and the fines' specific surface area.

As addressed in section 2.2.2.4, the relative movements between particles are enhanced by high matrix volume (matrix surplus) and high content of rounded and cubical particles. The higher the content of irregularly shaped particles, the higher the matrix volume needed to allow the particles to move freely. This relationship can be observed in the present results in Figure 4.9 (right), where the high plastic viscosity *(H)* of the particle dominated mix MU100 can be related to the high content of flaky and elongated particles.

4.4.5 Compressive strength

The compressive strength related to the different basic mixes is shown in Table 4.4. The minimum requirement of 45 MPa is met for all four basic mixes. The present results indicate that a high content of flaky and elongated particles is beneficial for the compressive strength. This finding is in agreement with the fact that crushed aggregates usually provide concretes with a higher mechanical strength than natural aggregates as the particles tend to have a higher roughness and surface area due to their shapes, contributing to improve their bonding to the remaining part of the concrete (the hardened matrix phase) [61]. The lower compressive strength achieved with mix MF50 can be attributed to the high free mica content of the sand

material MF. A high content of mica minerals is known to have a negative impact on the compressive strength [18] [21].

5 CONCLUSION

All the characterized sand materials are composed of similar rock types; primarily gneiss and granite and some dark- and feldspathic rocks. These rock types are known to be suitable as concrete aggregates, provided that the content of mica is not too high. Mica is in fact found in all characterized sand materials and the content is higher for the crushed sand materials, MF, MU1 and MU2, than the reference sand material, MR1. The content is especially high for the crushed sand material from the Follo Line, MF, which may be a direct result of the implementation of VSI in the crushing process. Despite the relatively high content of mica minerals in the crushed sand materials, MF and MU1, neither the concrete rheology study nor the compressive strength test showed significant unfavourable effects. Only a slight increase in flow resistance and a minor decrease in compressive strength was observed for the crushed sand material from the Follo Line, MF.

The present results have demonstrated that the implementation of VSI in the crushing process improves the particle shape quality of crushed sand materials by increasing the content of rounded and cubical particles. The reference sand material, MR1, which originates from a glaciofluvial and moraine deposit, has the highest particle shape quality, whereas the crushed sand materials from Ulriken, MU1 and MU2, which are produced without the implementation of VSI, have the poorest particle shape quality among the characterized sand materials. Both the rheological properties, i.e. slump-flow, yield stress and plastic viscosity, and the compressive strength are influenced by the particle shape quality. The rheological properties are affected negatively, whereas the compressive strength can be improved by high interparticle friction and irregularly shaped particles.

The present results have also demonstrated that the implementation of wet classification in the crushing process is essential to keep the fines content of crushed sand materials at an acceptable level. All the sand materials included in the concrete rheology study, MR1, MF and MU1, seem to have acceptable fines content with respect to both rheology and stability properties; the studied matrix materials possessed reasonable flow resistance values and none of the equivalent basic mixes showed signs of separation. It has been proven that the specific surface area of the fines of these sand materials is mainly governed by the grading and the content of the finest particles, especially particles ≤ approximately 20 μm, and to a lesser extent by the content of mica minerals and flaky/elongated particles.

This study has revealed that the fines of the reference sand material, $MR1_{\leq 0.125mm}$, has, surprisingly enough, the worst performance in the matrix phase in the sense that the mixes comprised of this material have the highest flow resistance values. This is associated to the fact that this type of fines has the highest specific surface area. On the other hand, it has been revealed that the mixes composed of this type of fines is less sensitive to variation in total surface area of fines, implying that this material would have had the best performance in the matrix phase *if* all the investigated fine materials had similar specific surface area. The fines of the crushed sand materials, $MF_{\leq 0.125mm}$ and $MU1_{\leq 0.125mm}$, have rather similar behaviour in terms of influence on matrix phase properties and sensitivity to surface area variation.

It has been shown that the basic mix composed of the crushed sand material from Ulriken, mix MU100, has the highest void content, whereas the basic mix composed of the reference sand material, mix MR100, has the lowest. This finding is in agreement with the fact that the crushed sand material from Ulriken, MU1, and the reference sand material, MR1, have the highest and the lowest content of flaky and elongated particles, respectively. As all basic mixes have been proportioned for a matrix volume of 430 mm, the matrix surplus is highest for mix MR100 and

lowest for mix MU100, i.e. decreasing with increasing content of flaky and elongated particles. In fact, the matrix volume in mix MU100 seems to be inadequate to fill all the voids.

The present results have revealed that the properties of the sand materials influence primarily the plastic viscosity and to a lesser extent the yield stress, the slump and the slump-flow. Furthermore, the results indicate that the main basic mixes, MR100, MF50 and MU50, are matrix dominated – mainly governed by the properties of the matrix phase, whereas the fourth basic mix MU100 is particle dominated – mainly governed by the properties of the particle phase. Hence, the relatively small variation in plastic viscosity among the mixes MR100, MF50 and MU50 can be ascribed to the rather small variation in flow resistance among the equivalent matrix materials. The flow resistance of the matrix phases seems to be predominantly governed by the fines content and the free mica content. On the other hand, the high plastic viscosity of mix MU100 can be associated to the high content of flaky and elongated particles of the crushed sand material MU1.

Based on the aforementioned findings, the "final" conclusion of this study can be drawn: Up to 50 % of the natural sand in sprayed concrete can be replaced with crushed rock materials from tunnelling, provided that the content of free mica is not too high and the content of fines is kept at an acceptable level with respect to both concrete stability and rheology. Such replacement is possible even for aggregates with a high content of flaky and elongated particles because the effect of particle shape quality is somewhat reduced for sprayed concrete, as basic mixes typically are proportioned with a high matrix volume. The effect of poor particle shape quality, that is, higher superplasticizer demand, higher yield stress and most importantly higher plastic viscosity, increases with increasing proportion of flaky and elongated particles. Hence, replacing all natural sand with crushed rock materials from tunnelling will be unreasonable technically, environmentally and economically, as this means even higher cement demand. However, it is believed that such replacement may be possible if sufficient efforts are made to improve the particle shape quality, such as the implementation of VSI in the crushing process.

6 FURTHER WORK

This study has a limited scope and the experimental work has many limitations. Hence, the "final" conclusion of this study is not 100 % certain and must be verified and extended by further work.

The rheological properties slump, slump-flow, *G* and *H* are parameters that only give an indication of the pumpability of the fresh concrete. Consequently, the present study should be extended by studies involving pumping of fresh concrete and evaluation of concrete pumpability. The importance of the different rheological properties for the pumpability of the fresh concrete should be further investigated. Furthermore, the concrete rheology study in the present study should be repeated with the same basic mixes but with fibres, as fibres are usually used in sprayed concrete for rock support and are known to have a negative effect on fresh concrete properties. In further studies, the yield stress and the plastic viscosity of the same matrix materials should be determined and compared with the present results to see if there are any direct correlations between these properties and the rheological properties of concrete. Further studies should also include a fifth basic mix with an aggregate composed of pure crushed sand from the Follo Line in order to address the advantage of applying VSI in the crushing process and to evaluate the possibility of producing sprayed concrete with pure crushed sand. An optimal proportion between crushed- and natural sand should also be investigated in further studies. Finally, the conclusion of this study should be reinforced and extended by studying more excavated rock materials from future tunnelling projects.

7 APPENDICES

Appendix A.1 – Grading declaration, CE-marking and DoP from Norstone

Side - 1 -

CE

1111

NorStone Årdal, 4137 Årdal, Norge

14

NS-EN 12620:2002+A1:2008+NA:2009

Tilslag for betong

Ytelseserklæring nr / Entydig identifikasjonskode

101718-115 001 Natur/knust 0/8mm (B) Gneis-Granitt

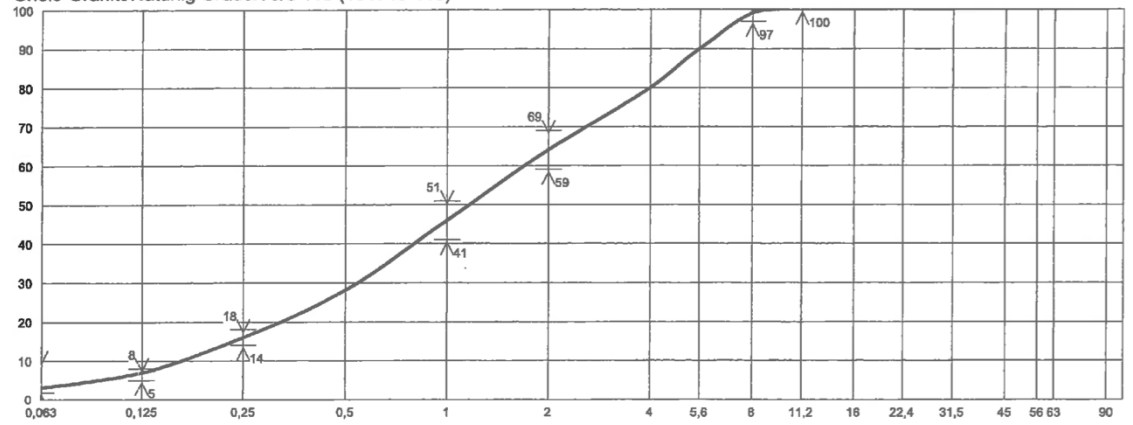
Standarder		Verdier	Kategorier
	Kornstørrelse		0/8
NS EN 933-1	Gradering		$G_{NG}90$
	Toleransekategori		-
	Kornform		
NS EN 933-3	Flisighetsindeks	-	FI_{NR}
NS EN 1097-6	**Korndensitet**	2,68 Mg/m³	2,66 Mg/m³ - 2,70 Mg/m³
NS EN 1097-6	**Vannabsorbsjon**	0,3%	$WA_{24}1$
NS-EN12620 F.2.3	**Motstand mot frysing og tining**	0,3	-
	Renhet		
NS EN 933-1	Finstoffinnhold	3%	f_{10}
NS EN 933-7	Skjellinnhold		SC_{IK}
NS EN 933-5	**Prosentandel knuste korn**		C_{IK}
	Sammensetning / innhold		
NS EN 1744-1§ 7	Klorider	0,000	$Cl_{0,02}$
NS EN 1744-1§ 11	Totalt innhold av svovel	0,00	S_1
NS EN 1744-1§ 12	Syreløselige sulfater	0,02	$AS_{0,2}$
NS-EN 1744-1§ 15	Bestanddeler som endrer stykknings- og herdingstiden av betong		Lysere
NB 21	**Alkalireaktivitet (sammeligningsverdi)**	0,9%	
NS EN 932-3	Petrografisk beskrivelse	Sand med knuste korn fra løssmasseforekomst. Hovedsakelig sammensatt av kubisk rundede/skarpkantede korn av granitt,gneis,feltspatiske bergarter og mørke bergarter.Løst belegg på kornoverflater, enkelte forvitrede korn og enkelte meget svake korn.	

NORSTONE
HEIDELBERGCEMENT Group

Material	Vare nr	Dato	Avdeling
0/8	101718-115	07.01.2014	NorStone Årdal

	Gjennomgang(%)																
	0,063	0,125	0,25	0,5	1	2	4	5,6	8	11,2	16	22,4	31,5	45	56	63	90
Typisk gradering	3,0	7,0	16,0	28,0	46,0	64,0	80,0	90,0	99,0	100,0							
Min.	2,0	5,0	14,0		41,0	59,0			97,0	100,0							
Max.	5,0	8,0	18,0		51,0	69,0			100,0								

Gneis-Granitt/Naturlig Gradert 0/8 115 (101718-115)



07.01.2014
Dato

Torstein Riskedal

Ytelseserklæring

I henhold til forordning (EU) nr. 305/2011 (byggevarer), vedlegg III

Ytelseserklæring nr:	**101718-115 001**			
Natur/knust	0/8mm (B)	Gneis-Granitt	Vare nr:	**101718-115**
Bruksområder for byggevaren(e):			**Tilslag for betong**	
Det eller de systemer for vurdering og kontroll av byggevarens konstante ytelse			**System 2+**	
Dersom ytelseserklæringen gjelder en byggevare som omfattes av en harmonisert Standard			**NS-EN 12620:2002+A1:2008+NA:2009**	
Sertifiseringsorganet:			**Kontrollrådet-1111**	
har utstedt sertifikat for produksjonskontrollen i samsvar med			**System 2+**	
basert på første-gangsrevisjon av produksjons-anlegget og produksjonskontrollen:			**1111-CPD-0007**	

NORSTONE
HEIDELBERGCEMENT Group
NorStone Årdal
NorStone Årdal, 4137 Årdal, Norge
www.norstone.no
Tlf:0047-51754200
Fax:0047-51754201

Harmonisert teknisk spesifikasjon	Standarder	Vesentlige egenskaper	Ytelse: Verdier	Ytelse: Kategorier
NS EN 12620:2002+A1:2008+NA:2009		**Kornstørrelse**		0/8
	NS EN 933-1	Gradering		$G_{NG}90$
		Toleransekategori		-
		Kornform		
	NS EN 933-3	Flisighetsindeks	-	FI_{NR}
	NS EN 933-4	Shape indeks	-	SI_{NR}
	NS EN 1097-6	**Korndensitet**	2,68 Mg/m³	2,66 Mg/m³ - 2,70 Mg/m³
	NS EN 1097-6 §8	**Vannabsorbsjon**	0,3%	$WA_{24}1$
	NS-EN12620 F.2.3	**Motstand mot frysing og tining**	0,3	-
		Renhet		
	NS EN 933-1	Finstoffinnhold	3 %	f_{10}
	NS EN 933-7	Skjellinnhold		SC_{IK}
		Motstand mot knusing		
	NS EN 1097-2 §5	Los Angeles-prøving		NPD
	NS EN 1097-2 §6	Slagprøving		NPD
		Motstand mot polering/slitasje		
	NS EN 1097-8	Poleringsverdi		NPD
	NS EN 1097-1	Motstand mot slitasje for grovt tilslag		NPD
	NS EN 1097-9	Motstand mot piggdekkslitasje		NPD
		Sammensetning / innhold		
	NS EN 1744-1§ 7	Klorider	0,000	$Cl_{0,02}$
	NS EN 1744-1§ 11	Totalt innhold av svovel	0,00	S_1
	NS EN 1744-1§ 12	Syreløselige sulfater	0,02	$AS_{0,2}$
	NS EN 1744-1§ 15	Bestanddeler som endrer stykknings- og herdingstiden av betong		Lysere
	NB21	**Alkalireaktivitet (sammeligningsverdi)**	0,9%	
	NS EN 932-3	**Petrografisk beskrivelse**	Sand med knuste korn fra løssmasseforekomst. Hovedsakelig sammensatt av kubisk rundede/skarpkantede korn av granitt,gneis,feltspatiske bergarter og mørke bergarter.Løst belegg på kornoverflater, enkelte forvitrede korn og enkelte meget svake korn.	

Ytelsen for denne varen som angitt ovenfor, er i samsvar med spesifikasjonene for produktet angitt i tabellen.

Denne ytelseserklæringen er utstedt på eget ansvar av produsenten, NorStone Årdal

Undertegnet for og på vegne av produsenten av:

Torstein Riskedal, lab.leder

(navn og stilling)

Torstein Riskedal

Årdal 07.01.2014

(Sted og utstedelsesdato)

(Underskrift)

NORSTONE
HEIDELBERGCEMENT Group

Dato:	24.11.2014	**Kunde:**	Sintef
Materiale:	0/8 mm System 2+	**Havn:**	
Varenr:	101718-115	**Båt:**	Big-bags
Følgeseddel nr:			

Test	NS-EN 933-1	Laboratorium	NorStone Årdal
Identifikasjon av prøven	0/8 mm 115	Operatør	Riskedal
Dato mottatt/uttatt	24.11.2014	Dato utført	24.11.2014
Metod (angi)	[ ] Vasking og sikting	Standard	NS-EN 12620
	[x] Tørrsikting	Sertifikat:	1111-CPD-0007
		Produksjonssted	NorStone Årdal

Total tørr masse M_1 = 729,7 g

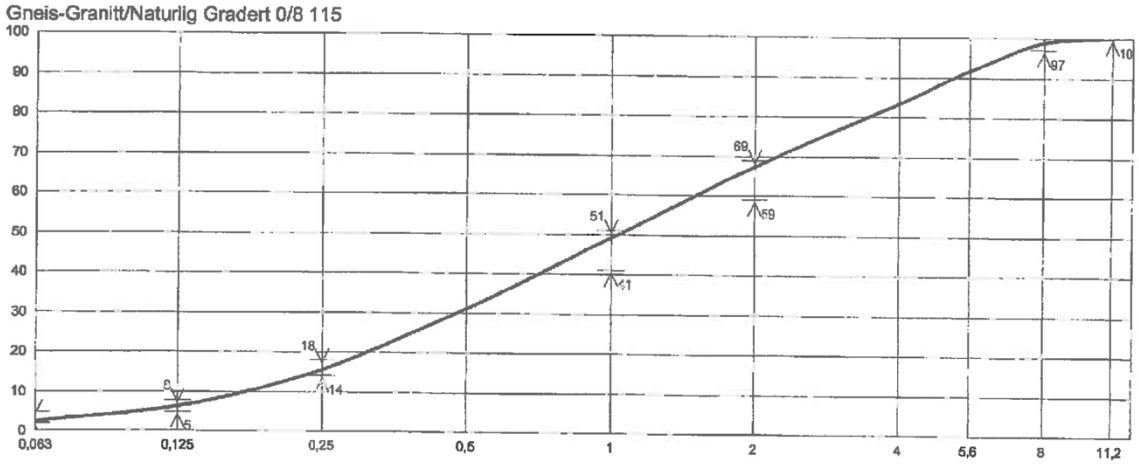
Tørr masse etter vasking M_2 = g

Tørr masse av Finstoff fjernet ved vasking $M_1 - M_2$ = g

Vanninnhold (%) NS 1097-5 =

			Gjennomgang			
Sikteåpning (mm)	**Masse tilbakehold** (g)	**Prosentandel** (%)	**Akkumulert Prosentandel** (%)	**Idealkurve** (%)	**Min** (%)	**Max** (%)
11,2			100,0	100,0	100,0	
8	8,8	1,2	98,8	99,0	97,0	100,0
5,6	52,0	7,1	91,7	90,0		
4	60,7	8,4	83,3	80,0		
2	117,5	16,1	67,2	64,0	59,0	69,0
1	132,4	18,1	49,1	46,0	41,0	51,0
0,5	131,4	18,0	31,1	28,0		
0,25	113,5	15,6	15,5	16,0	14,0	18,0
0,125	68,4	9,3	6,2	7,0	5,0	8,0
0,063	27,4	3,8	2,4	3,0	2,0	5,0
< 0,063	17,5	2,4				
Sum	729,6	100.0	0,0	*< 1% Prosentsats materiale tapt*		

Gneis-Granitt/Naturlig Gradert 0/8 115



Appendix A.1
Grading declaration, CE marking and DoP from NorStone

CE
1111

NorStone Årdal, 4137 Årdal, Norge

12

NS-EN 12620:2002+A1:2008+NA:2009

Tilslag for betong

Ytelseserklæring nr / Entydig identifikasjonskode

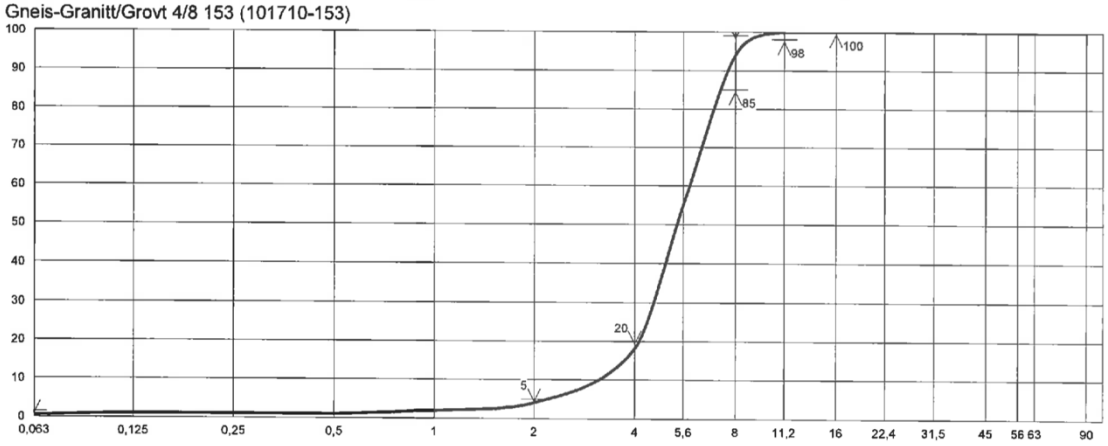
101710-153 002 100 Knust-Natur 4/8mm (B) Gneis-Granitt

Standarder		**Verdier**	**Kategorier**
	Kornstørrelse		4/8
NS EN 933-1	Gradering		$G_C85/20$
	Toleransekategori		-
	Kornform		
NS EN 933-3	Flisighetsindeks	3%	FI_{10}
NS EN 1097-6	**Korndensitet**	2,67 Mg/m³	2,65 Mg/m³ - 2,69 Mg/m³
NS EN 1097-6	**Vannabsorbsjon**	0,5%	$WA_{24}1$
NS-EN12620 F.2.3	**Motstand mot frysing og tining**	0,5	F_{NR}
	Renhet		
NS EN 933-1	Finstoffinnhold	0,5%	$f_{1,5}$
NS EN 933-7	Skjellinnhold		SC_{10}
NS EN 933-5	**Prosentandel knuste korn**		C_{IK}
	Sammensetning / innhold		
NS EN 1744-1§ 7	Klorider		$Cl_{0,02}$
NS EN 1744-1§ 11	Totalt innhold av svovel		
NS EN 1744-1§ 12	Syreløselige sulfater	0,02	$AS_{0,2}$
NS-EN 1744-1§ 15	Bestanddeler som endrer stυrknings- og herdingstiden av betong		Lysere
NB 21	**Alkalireaktivitet (sammeligningsverdi)**	0,8%	
ASTM C1260-14	**Accelereret mørtelprismeekspansion**	0,01%	<0.10%
NS EN 932-3	Petrografisk beskrivelse	Singel med knuste korn fra løssmasseforekomst. Hovedsakelig sammensatt av kubisk rundede/skarpkantede korn av granitt, gneis, feltspatiske bergarter og mørke bergarter. Løst belegg på kornoverflater, ingen forvitrede korn og ingen meget svake korn.	

Material	Vare nr	Dato	Avdeling
4/8	101710-153	27.09.2016	NorStone Årdal

	Gjennomgang(%)																
	0,063	0,125	0,25	0,5	1	2	4	5,6	8	11,2	16	22,4	31,5	45	56	63	90
Typisk gradering	0,5	1,0	1,0	1,0	2,0	4,0	18,0	55,0	94,0	100,0							
Min.									85,0	98,0	100,0						
Max.	1,5					5,0	20,0		99,0	100,0							

Gneis-Granitt/Grovt 4/8 153 (101710-153)



27.09.2016	S. Tengesdal
Dato	Prepared by

Ytelseserklæring

I henhold til forordning (EU) nr. 305/2011 (byggevarer), vedlegg III

Ytelseserklæring nr: **101710-153 002**		NORSTONE HEIDELBERGCEMENT Group
100 Knust-Natur 4/8mm (B) Gneis-Granitt	Vare nr: **101710-153**	
Bruksområder for byggevaren(e):	**Tilslag for betong**	NorStone Årdal
Det eller de systemer for vurdering og kontroll av byggevarens konstante ytelse	**System 2+**	
Dersom ytelseserklæringen gjelder en byggevare som omfattes av en harmonisert Standard	**NS-EN 12620:2002+A1:2008+NA:2009**	NorStone Årdal, 4137 Årdal, Norge
Sertifiseringsorganet:	**Kontrollrådet-1111**	www.norstone.no
har utstedt sertifikat for produksjonskontrollen i samsvar med	**System 2+**	Tlf:0047-51754200
basert på førstegangsrevisjon av produksjons-anlegget og produksjonskontrollen:	**1111-CPD-0007**	Tlf:0047-51754201
Ytelseserklæring arkiveres i ti år.		

Harmonisert teknisk spesifikasjon	Standarder	Vesentlige egenskaper	Ytelse	
			Verdier	Kategorier
NS EN 12620:2002+A1:2008+NA:2009		**Kornstørrelse**		4/8
	NS EN 933-1	Gradering		$G_C85/20$
		Toleransekategori		-
		Kornform		
	NS EN 933-3	Flisighetsindeks	3%	FI_{10}
	NS EN 933-4	Shape indeks	-	NPD
	NS EN 1097-6	**Korndensitet**	2,67 Mg/m³	2,65 Mg/m³ - 2,69 Mg/m³
	NS EN 1097-6 §8	**Vannabsorbsjon**	0,5%	$WA_{24}1$
	NSEN 12620 F.2.3	**Motstand mot frysing og tining**	0,5	F_{NR}
		Renhet		
	NS EN 933-1	Finstoffinnhold	0,5 %	$f_{1,5}$
	NS EN 933-7	Skjellinnhold		SC_{10}
		Motstand mot knusing		
	NS EN 1097-2 §5	Los Angeles-prøving	24	LA_{30}
	NS EN 1097-2 §6	Slagprøving		NPD
		Motstand mot polering/slitasje		
	NS EN 1097-8	Poleringsverdi		NPD
	NS EN 1097-1	Motstand mot slitasje for grovt tilslag		NPD
	NS EN 1097-9	Motstand mot piggdekkslitasje		NPD
		Sammensetning / innhold		
	NS EN 1744-1§ 7	Klorider		$Cl_{0,02}$
	NS EN 1744-1§ 11	Totalt innhold av svovel		
	NS EN 1744-1§ 12	Syreløselige sulfater	0,02	$AS_{0,2}$
	NS EN 1744-1§ 15	Bestanddeler som endrer stykningss- og herdingstiden av betong		Lysere
	NB21	**Alkalireaktivitet (sammeligningsverdi)**	0,8%	
	ASTM C1260-14	**Accelereret mørtelprismeekspansion**	0,01%	<0.10%
	NS-EN 932-3	**Innhold av kalkstein**	0,0%	
	NS EN 932-3	**Petrografisk beskrivelse**	Singel med knuste korn fra løssmasseforekomst. Hovedsakelig sammensatt av kubisk rundede/skarpkantede korn av granitt, gneis, feltspatiske bergarter og mørke bergarter. Løst belegg på kornoverflater, ingen forvitrede korn og ingen meget svake korn.	

Ytelsen for denne varen som angitt ovenfor, er i samsvar med spesifikasjonene for produktet angitt i tabellen. Denne ytelseserkl¿ringen er utstedt på eget ansvar av produsenten, NorStone Årdal. Undertegnet for og på vegne av produsenten av:

Svein Johan Mæland, Site Manager
(navn og stilling)

Årdal 27.09.2016
(Sted og utstedelsesdato)

Svein Mæland
(Underskrift)

NORSTONE
HEIDELBERGCEMENT Group

Dato:	01.02.2017	**Kunde:**	Sintef
Materiale:	4/8 mm System 2+	**Havn:**	
Varenr:	101710-153	**Båt:**	
Følgeseddel nr:			

Test	NS-EN 933-1	Laboratorium	NorStone Årdal
Identifikasjon av prøven	4/8 mm 153	Operatør	Dahle
Dato mottatt/uttatt	01.02.2017	Dato utført	01.02.2017
Metod (angi)	[ ] Vasking og sikting	Standard	NS-EN 12620
	[x] Tørrsikting	Sertifikat:	1111-CPD-0007
		Produksjonssted	NorStone Årdal

Total tørr masse M_1 = 100,0 g

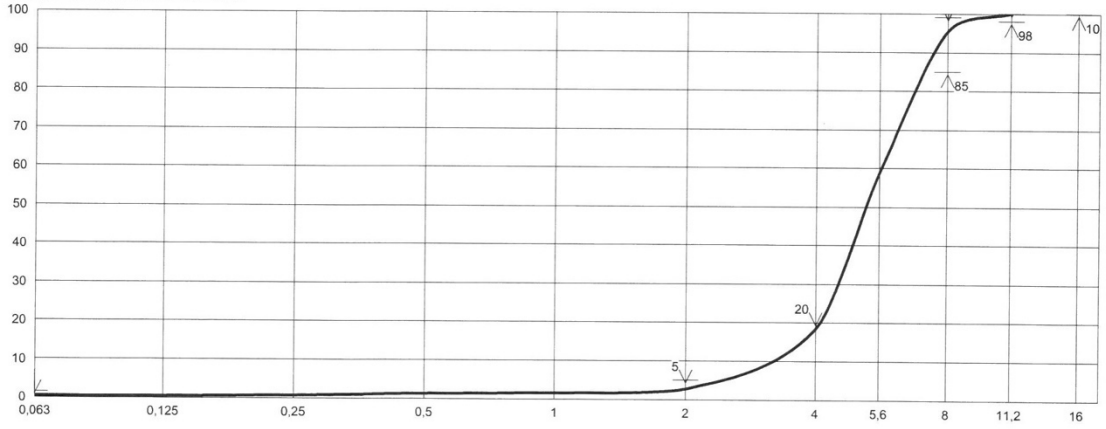
Tørr masse etter vasking M_2 = g

Tørr masse av Finstoff fjernet ved vasking $M_1 - M_2$ = g

Vanninnhold (%) NS 1097-5 =

			Gjennomgang			
Sikteåpning (mm)	**Masse tilbakehold** (g)	**Prosentandel** (%)	**Akkumulert Prosentandel** (%)	**Idealkurve** (%)	**Min** (%)	**Max** (%)
16					100,0	
11,2			100,0	100,0	98,0	100,0
8	4,8	4,8	95,2	94,0	85,0	99,0
5,6	36,5	36,5	58,7	55,0		
4	40,3	40,3	18,4	18,0		20,0
2	15,8	15,8	2,6	4,0		5,0
1	1,1	1,1	1,5	2,0		
0,5	0,4	0,4	1,1	1,0		
0,25	0,4	0,4	0,7	1,0		
0,125	0,3	0,3	0,4	1,0		
0,063	0,1	0,1	0,3	0,5		1,5
< 0,063	0,3	0,3				
Sum	100,0	100.0	0,0	*< 1% Prosentsats materiale tapt*		

Gneis-Granitt/Grovt 4/8 153



Appendix A.2 – The mix design of the basic mixes

Mix MR100

Proporsjonering av betong SKANSKA

Prosjekt	Kortreist stein - prosjektnr. 102013212
Reseptnummer	1 - Årdal
Tilsiktet kvalitet	B35 M45
Utført av	Judy Luong (NTNU)
Dato	13/03/2017

Initialparametre	Verdi
m = v/(c+Σkp)	0,42
Luftinnhold	3,0 %

Sementtype	Andel	Andel klinker	Andel FA	Andel slagg	[kg/m^3]	Alkalier	Klorider
Norcem Standard FA	100,0 %	78,0 %	18,0 %	0,0 %	3000	1,4 %	0,1 %
	0,0 %	0,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %
	0,0 %	0,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %

Tilsetningsmaterialer	Type	Andel (av b)	k	[kg/m^3]	Alkalier	Klorider
Elkem Microsilica	Silika	9,0 %	2,0	2200	0,1 %	0,1 %
	FA	0,0 %	0,7	2200	1,0 %	0,3 %
	Slagg	0,0 %	0,6	1000	1,0 %	0,3 %

Tilsetningsstoff	% av b	[kg/m^3]	Tørrstoff	[kg/m^3] TS	Alkalier	Klorider
Sika SSP 2000	0,8 %	1055	24,0 %	1277	0,6 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %

Fiber	Vol %	[kg/m3]
	0,0 %	7800
	0,0 %	1050

Matriks	Verdi
Ønsket matriksvolum [l/m^3]	430
Oppnådd matriksvolum [l/m^3]	430
Klinkerandel i bindemiddel	71,0 %
Total FA- andel av bindemiddel	16,4 %
Total slaggandel av bindemiddel	0,0 %
Volum sementlim [l/m^3]	394,5
Effektivt vanninnhold [l/m^3]	224,8
v/p	0,38
Effektivt bindemiddel [kg/m^3]	535
Totalt bindemiddel [kg/m^3]	491

Appendix A.2
The mix design of the basic mixes

Blandeskjema SKANSKA

Prosjekt	Kortreist stein - prosjektnr. 102013212
Reseptnummer	1 - Årdal
Tilsiktet kvalitet	B35 M45

Blandevolum	30 liter
Dato:	29.03.2017
Tidspunkt for vanntilsetning:	10.45
Ansvarlig:	E.J. og R.L (SINTEF)
Utført av:	E.J., R.L, S.R og T.S (SINTEF)

Materialer	**Resept** kg/m³	**Sats** kg	**Fukt*** %	**Korr.** kg	**Oppveid**** kg	
Norcem Standard FA	446,8	13,403			13,403	
	0,0	0,000			0,000	
	0,0	0,000			0,000	
Elkem Microsilica	44,2	1,326	0,0	0,000	1,326	
0	0,0	0,000			0,000	
	0,0	0,000			0,000	
Fritt vann	224,8	6,743		-1,755	4,988	5,126
Absorbert vann	4,6	0,139			0,139	
Årdal 0/8 naturlig	1542,3	46,269	3,6	1,666	47,935	
Årdal 4/8mm naturlig	0,0	0,000	0,0	0,000	0,000	
Ulriken 0/4mm vasket	0,0	0,000	0,0	0,000	0,000	
Ulriken 0/4mm uvasket	0,0	0,000	0,0	0,000	0,000	
Follob. 0/8mm vasket	0,0	0,000	0,0	0,000	0,000	
Grenseverdier minimum, NB7	0,0	0,000	0,0	0,000	0,000	
Grenseverdier maksimum, NB7	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Sika SSP 2000	3,9	0,118	76	0,090	0,118	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000			0,000	
	0,0	0,000			0,000	

*Se fotnote på delark "Resept"

** NB! Våte mengder, også for silikaslurry

Sammensatt tilslag

Fraksjon	Navn	Densitet [kg/m³]	Abs. fukt [%]	Alk. reakt. Sv[%]	Klorider [%]	Andel volum	Andel vekt	Bruk
I	Årdal 0/8 naturlig	2680	0,3	0,0	0,00	1,000	1,000	ok
II	Årdal 4/8mm naturlig	2670	0,3	0,0	0,00	0,000	0,000	
III	Ulriken 0/4mm vasket	2960	0,1	0,0	0,00	0,000	0,000	
IV	Ulriken 0/4mm uvasket	2960	0,1	0,0	0,00	0,000	0,000	
V	Follob. 0/8mm vasket	2760	0,2	0,0	0,00	0,000	0,000	
VI	Grenseverdier minimum, N	2700	0,0	0,0	0,00	0,000	0,000	
VII	Grenseverdier maksimum,	2700	0,0	0,0	0,00	0,000	0,000	
VIII		2700	0,0	0,0	0,00	0,000	0,000	
IX		2700	0,0	0,0	0,00	0,000	0,000	
X		2700	0,0	0,0	0,00	0,000	0,000	
Sammensatt		2680		0,0	0,00	1,000	1,000	

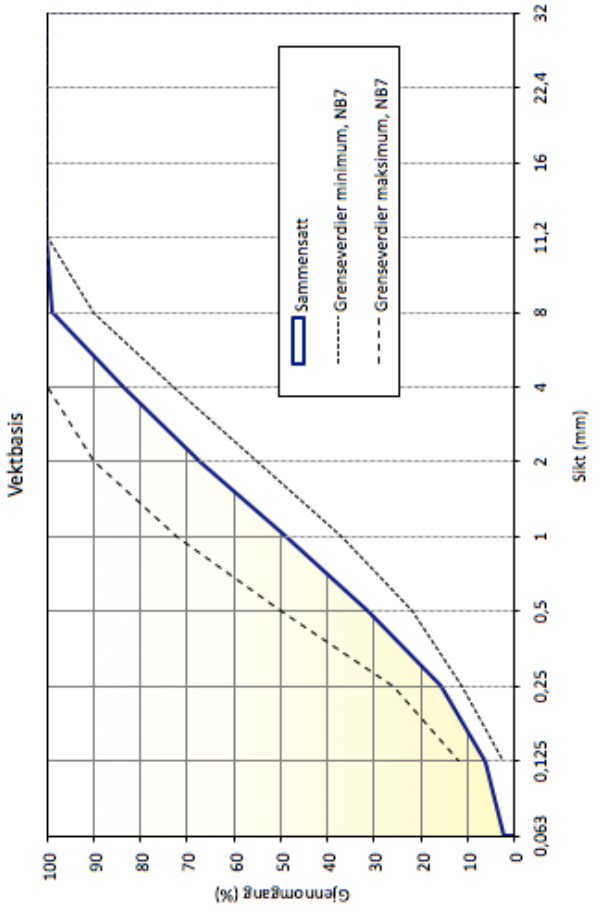
Finhetsmoduler	
FM_{vekt} =	3,02
FM_{vol} =	3,02
FM_{ref} =	3,02
FMg =	5,55

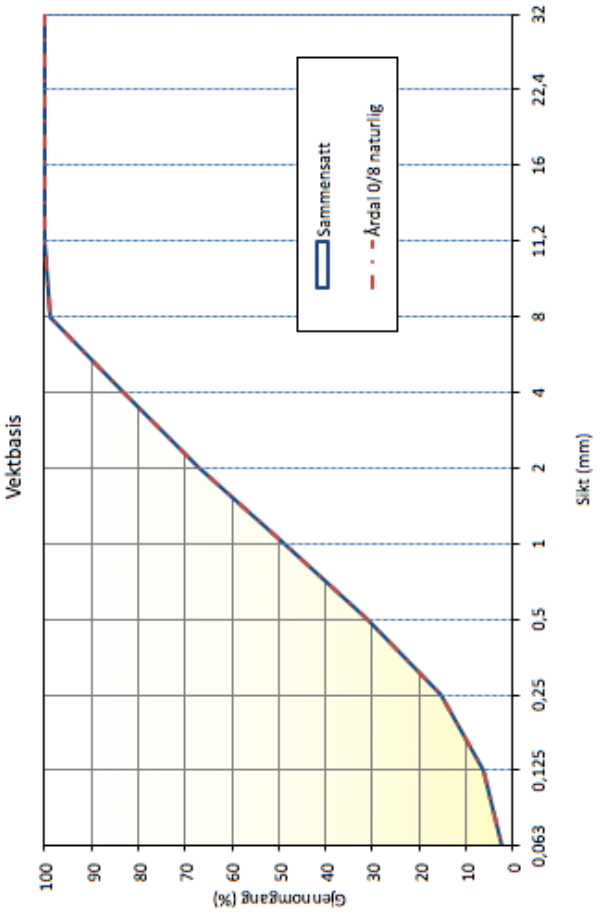
Tilpass til ref. gradering, Ctrl T

Sett ref. gradering, Ctrl R

Tilpass til FMg, Ctrl F

Åpning	Gjennomgang vol.[%]	Gjennomgang vekt [%]	Ref. grad. [vol. %]	Vekt ved tilpasning
32	100,0	100,0	100,0	1
22,4	100,0	100,0	100,0	1
16	100,0	100,0	100,0	1
11,2	100,0	100,0	100,0	1
8	98,8	98,8	98,8	1
4	83,3	83,3	83,3	1
2	67,2	67,2	67,2	1
1	49,1	49,1	49,1	2
0,5	31,1	31,1	31,1	2
0,25	15,5	15,5	15,5	2
0,125	6,2	6,2	6,2	2
0,063	2,4	2,4	2,4	2





Mix MF50

Proporsjonering av betong SKANSKA

Prosjekt	Kortreist stein - prosjektnr. 102013212
Reseptnummer	2 - Follobanen
Tilsiktet kvalitet	B35 M45
Utført av	Judy Luong (NTNU)
Dato	13/03/2017

Initialparametre	Verdi
m = v/(c+Σkp)	0,42
Luftinnhold	3,0 %

Sementtype	Andel	Andel klinker	Andel FA	Andel slagg	[kg/m^3]	Alkalier	Klorider
Norcem Standard FA	100,0 %	78,0 %	18,0 %	0,0 %	3000	1,4 %	0,1 %
	0,0 %	0,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %
	0,0 %	0,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %

Tilsetningsmaterialer	Type	Andel (av b)	k	[kg/m^3]	Alkalier	Klorider
Elkem Microsilica	Silika	9,0 %	2,0	2200	0,1 %	0,1 %
	FA	0,0 %	0,7	2200	1,0 %	0,3 %
	Slagg	0,0 %	0,6	1000	1,0 %	0,3 %

Tilsetningsstoff	% av b	[kg/m^3]	Tørrstoff	[kg/m^3] TS	Alkalier	Klorider
Sika SSP 2000	0,8 %	1055	24,0 %	1277	0,6 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %

Fiber	Vol %	[kg/m3]
	0,0 %	7800
	0,0 %	1050

Matriks	Verdi
Ønsket matriksvolum [l/m^3]	430
Oppnådd matriksvolum [l/m^3]	430
Klinkerandel i bindemiddel	71,0 %
Total FA- andel av bindemiddel	16,4 %
Total slaggandel av bindemiddel	0,0 %
Volum sementlim [l/m^3]	392,5
Effektivt vanninnhold [l/m^3]	223,6
v/p	0,38
Effektivt bindemiddel [kg/m^3]	532
Totalt bindemiddel [kg/m^3]	488

Appendix A.2
The mix design of the basic mixes

Blandeskjema

SKANSKA

Prosjekt	Kortreist stein - prosjektnr. 102013212
Reseptnummer	2 - Follobanen
Tilsiktet kvalitet	B35 M45

Blandevolum	30 liter
Dato:	29.03.2017
Tidspunkt for vanntilsetning:	13.15
Ansvarlig:	E.J. og R.L. (SINTEF)
Utført av:	E.J., R.L. S.R. og T.S. (SINTEF)

Materialer	Resept kg/m³	Sats kg	Fukt* %	Korr. kg	Oppveid** kg	
Norcem Standard FA	444,5	13,335			13,335	
	0,0	0,000			0,000	
	0,0	0,000			0,000	
Elkem Microsilica	44,0	1,319	0,0	0,000	1,319	
0	0,0	0,000			0,000	
	0,0	0,000			0,000	
Fritt vann	223,6	6,709		-1,620	5,089	5,206
Absorbert vann	3,9	0,118			0,118	
Årdal 0/8mm naturlig	784,8	23,545	3,6	0,848	24,392	
Årdal 4/8mm naturlig	0,0	0,000	0,0	0,000	0,000	
Ulriken 0/4mm vasket	0,0	0,000	0,0	0,000	0,000	
Ulriken 0/4mm uvasket	0,0	0,000	0,0	0,000	0,000	
Follob. 0/8mm vasket	785,6	23,568	2,9	0,683	24,252	
Grenseverdier minimum, NB7	0,0	0,000	0,0	0,000	0,000	
Grenseverdier maksimum, NB7	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Sika SSP 2000	3,9	0,117	76	0,089	0,117	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000			0,000	
	0,0	0,000			0,000	

*Se fotnote på delark "Resept"

** NB! Våte mengder, også for silikaslurry

Sammensatt tilslag

Fraksjon	Navn	Densitet [kg/m³]	Abs. fukt [%]	Alk. reakt. Sv[%]	Klorider [%]	Andel volum	Andel vekt	Bruk
I	Årdal 0/8mm naturlig	2680	0,3	0,0	0,00	0,507	0,500	ok
II	Årdal 4/8mm naturlig	2670	0,3	0,0	0,00	0,000	0,000	ok
III	Ulriken 0/4mm vasket	2960	0,1	0,0	0,00	0,000	0,000	
IV	Ulriken 0/4mm uvasket	2960	0,1	0,0	0,00	0,000	0,000	
V	Follob. 0/8mm vasket	2760	0,2	0,0	0,00	0,493	0,500	ok
VI	Grenseverdier minimum, N	2700	0,0	0,0	0,00	0,000	0,000	
VII	Grenseverdier maksimum,	2700	0,0	0,0	0,00	0,000	0,000	
VIII		2700	0,0	0,0	0,00	0,000	0,000	
IX		2700	0,0	0,0	0,00	0,000	0,000	
X		2700	0,0	0,0	0,00	0,000	0,000	
Sammensatt		2719		0,0	0,00	1,000	1,000	

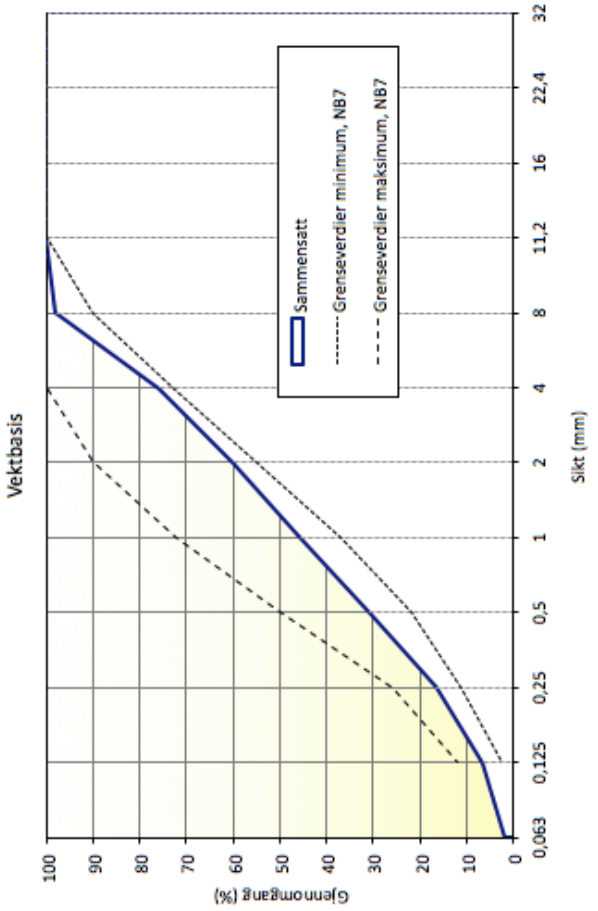
Finhetsmoduler	
FM_{vekt} =	3,20
FM_{vol} =	3,20
FM_{ref} =	3,02
FMg =	5,55

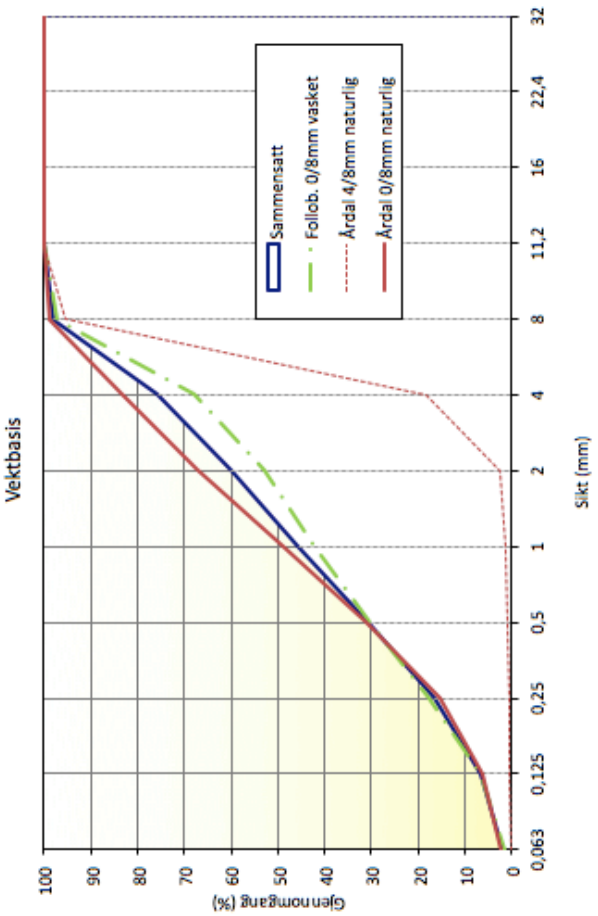
Tilpass til ref. gradering, Ctrl T

Sett ref. gradering, Ctrl R

Tilpass til FMg, Ctrl F

Åpning	Gjennomgang vol.[%]	Gjennomgang vekt [%]	Ref. grad. [vol. %]	Vekt ved tilpasning
32	100,0	100,0	100,0	1
22,4	100,0	100,0	100,0	1
16	100,0	100,0	100,0	1
11,2	100,0	100,0	100,0	1
8	98,1	98,1	98,8	1
4	75,8	75,7	83,3	1
2	60,1	60,0	67,2	1
1	45,8	45,7	49,1	2
0,5	30,8	30,8	31,1	2
0,25	16,5	16,6	15,5	2
0,125	6,5	6,5	6,2	2
0,063	2,0	2,0	2,4	2





Mix MU50

Proporsjonering av betong SKANSKA

Prosjekt	Kortreist stein - prosjektnr. 102013212
Reseptnummer	3 - Ulriken (50/50)
Tilsiktet kvalitet	B35 M45
Utført av	Judy Luong (NTNU)
Dato	13/03/2017

Initialparametre	**Verdi**
m = v/(c+Σkp)	0,42
Luftinnhold	3,0 %

Sementtype	**Andel**	**Andel klinker**	**Andel FA**	**Andel slagg**	**[kg/m^3]**	**Alkalier**	**Klorider**
Norcem Standard FA	100,0 %	78,0 %	18,0 %	0,0 %	3000	1,4 %	0,1 %
	0,0 %	0,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %
	0,0 %	0,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %

Tilsetningsmaterialer	**Type**	**Andel (av b)**	**k**	**[kg/m^3]**	**Alkalier**	**Klorider**
Elkem Microsilica	Silika	9,0 %	2,0	2200	0,1 %	0,1 %
	FA	0,0 %	0,7	2200	1,0 %	0,3 %
	Slagg	0,0 %	0,6	1000	1,0 %	0,3 %

Tilsetningsstoff	**% av b**	**[kg/m^3]**	**Tørrstoff**	**[kg/m^3] TS**	**Alkalier**	**Klorider**
Sika SSP 2000	0,8 %	1055	24,0 %	1277	0,6 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %

Fiber	**Vol %**	**[kg/m3]**
	0,0 %	7800
	0,0 %	1050

Matriks	**Verdi**
Ønsket matriksvolum [l/m^3]	430
Oppnådd matriksvolum [l/m^3]	430
Klinkerandel i bindemiddel	71,0 %
Total FA- andel av bindemiddel	16,4 %
Total slaggandel av bindemiddel	0,0 %
Volum sementlim [l/m^3]	390,9
Effektivt vanninnhold [l/m^3]	222,7
v/p	0,37
Effektivt bindemiddel [kg/m^3]	530
Totalt bindemiddel [kg/m^3]	487

Appendix A.2
The mix design of the basic mixes

Blandeskjema SKANSKA

Prosjekt	Kortreist stein - prosjektnr. 102013212
Reseptnummer	3 - Ulriken (50/50)
Tilsiktet kvalitet	B35 M45

Blandevolum	30 liter
Dato:	29.03.2017
Tidspunkt for vanntilsetning:	14.20
Ansvarlig:	E.J. og R.L (SINTEF)
Utført av:	E.J., R.L, S.R. og T.S (SINTEF)

Materialer	Resept kg/m³	Sats kg	Fukt* %	Korr. kg	Oppveid** kg	
Norcem Standard FA	442,7	13,282			13,282	
	0,0	0,000			0,000	
	0,0	0,000			0,000	
Elkem Microsilica	43,8	1,314	0,0	0,000	1,314	
0	0,0	0,000			0,000	
	0,0	0,000			0,000	
Fritt vann	222,7	6,682		-1,574	5,108	5,210
Absorbert vann	3,4	0,102			0,102	
Årdal 0/8 naturlig	809,6	24,288	3,6	0,874	25,163	
Årdal 4/8mm naturlig	81,0	2,429	0,8	0,019	2,448	
Ulriken 0/4mm vasket	730,1	21,903	2,7	0,591	22,494	
Ulriken 0/4mm uvasket	0,0	0,000	0,0	0,000	0,000	
Follob. 0/8mm vasket	0,0	0,000	0,0	0,000	0,000	
Grenseverdier minimum, NB7	0,0	0,000	0,0	0,000	0,000	
Grenseverdier maksimum, NB7	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Sika SSP 2000	3,9	0,117	76	0,089	0,117	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000			0,000	
	0,0	0,000			0,000	

*Se fotnote på delark "Resept"

** NB! Våte mengder, også for silikaslurry

Sammensatt tilslag

Fraksjon	Navn	Densitet [kg/m³]	Abs. fukt [%]	Alk. reakt. Sv[%]	Klorider [%]	Andel volum	Andel vekt	Bruk
I	Årdal 0/8 naturlig	2680	0,3	0,0	0,00	0,522	0,500	ok
II	Årdal 4/8mm naturlig	2670	0,3	0,0	0,00	0,052	0,050	ok
III	Ulriken 0/4mm vasket	2960	0,1	0,0	0,00	0,426	0,450	ok
IV	Ulriken 0/4mm uvasket	2960	0,1	0,0	0,00	0,000	0,000	ok
V	Follob. 0/8mm vasket	2760	0,2	0,0	0,00	0,000	0,000	
VI	Grenseverdier minimum, N	2700	0,0	0,0	0,00	0,000	0,000	
VII	Grenseverdier maksimum,	2700	0,0	0,0	0,00	0,000	0,000	
VIII		2700	0,0	0,0	0,00	0,000	0,000	
IX		2700	0,0	0,0	0,00	0,000	0,000	
X		2700	0,0	0,0	0,00	0,000	0,000	
Sammensatt		2799		0,0	0,00	1,000	1,000	

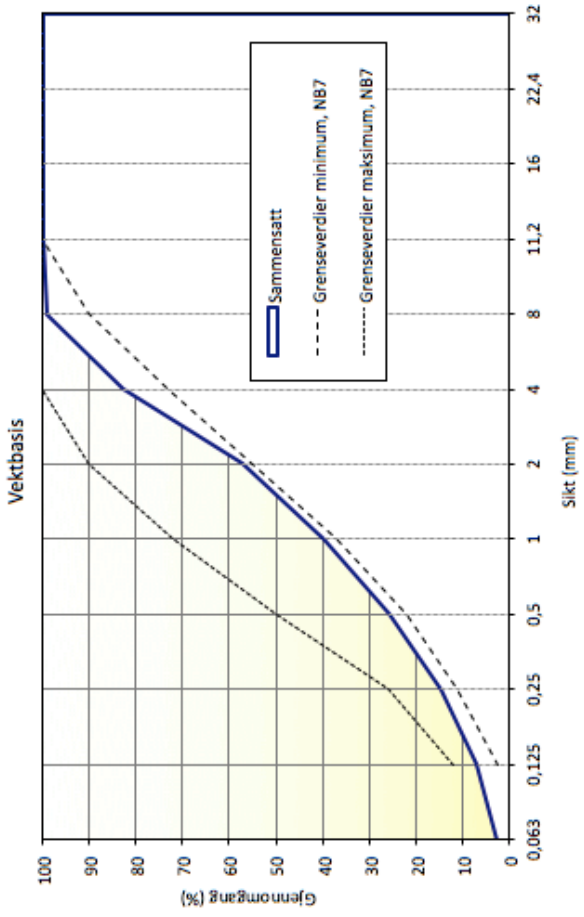
Finhetsmoduler	
FM_{vekt} =	3,28
FM_{vol} =	3,27
FM_{ref} =	3,02
FMg =	5,55

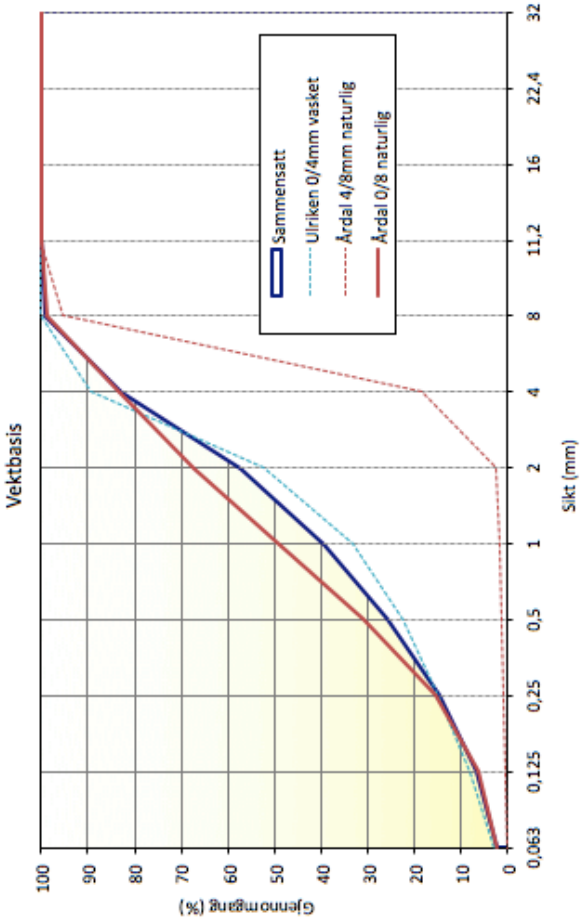
Tilpass til ref. gradering, Ctrl T

Sett. ref. gradering, Ctrl R

Tilpass til FMg, Ctrl F

Åpning	Gjennomgang vol.[%]	Gjennomgang vekt [%]	Ref. grad. [vol. %]	Vekt ved tilpasning
32	100,0	100,0	100,0	1
22,4	100,0	100,0	100,0	1
16	100,0	100,0	100,0	1
11,2	100,0	100,0	100,0	1
8	99,1	99,2	98,8	1
4	82,4	82,7	83,3	1
2	57,6	57,4	67,2	1
1	39,8	39,5	49,1	2
0,5	25,9	25,8	31,1	2
0,25	14,5	14,6	15,5	2
0,125	6,7	6,8	6,2	2
0,063	2,5	2,5	2,4	2





Mix MU100

Proporsjonering av betong SKANSKA

Prosjekt	Kortreist stein - prosjektnr. 102013212
Reseptnummer	4 - Ulriken (100/0)
Tilsiktet kvalitet	B35 M45
Utført av	Judy Luong (NTNU)
Dato	04/04.2017

Initialparametre	Verdi
m = v/(c+Σkp)	0,42
Luftinnhold	3,0 %

Sementtype	Andel	Andel klinker	Andel FA	Andel slagg	[kg/m^3]	Alkalier	Klorider
Norcem Standard FA	100,0 %	78,0 %	18,0 %	0,0 %	3000	1,4 %	0,1 %
	0,0 %	0,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %
	0,0 %	0,0 %	0,0 %	0,0 %	1000	0,0 %	0,0 %

Tilsetningsmaterialer	Type	Andel (av b)	k	[kg/m^3]	Alkalier	Klorider
Elkem Microsilica	Silika	9,0 %	2,0	2200	0,1 %	0,1 %
	FA	0,0 %	0,7	2200	1,0 %	0,3 %
	Slagg	0,0 %	0,6	1000	1,0 %	0,3 %

Tilsetningsstoff	% av b	[kg/m^3]	Tørrstoff	[kg/m^3] TS	Alkalier	Klorider
Sika SSP 2000	0,8 %	1055	24,0 %	1277	0,6 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %
	0,0 %	1000	100,0 %	1000	0,0 %	0,0 %

Fiber	Vol %	[kg/m3]
	0,0 %	7800
	0,0 %	1050

Matriks	Verdi
Ønsket matriksvolum [l/m^3]	430
Oppnådd matriksvolum [l/m^3]	430
Klinkerandel i bindemiddel	71,0 %
Total FA- andel av bindemiddel	16,4 %
Total slaggandel av bindemiddel	0,0 %
Volum sementlim [l/m^3]	387,0
Effektivt vanninnhold [l/m^3]	220,5
v/p	0,36
Effektivt bindemiddel [kg/m^3]	525
Totalt bindemiddel [kg/m^3]	482

Blandeskjema

SKANSKA

Prosjekt	Kortreist stein - prosjektnr. 102013212
Reseptnummer	4 - Ulriken (100/0)
Tilsiktet kvalitet	B35 M45

Blandevolum	30 liter
Dato:	06.04.2017
Tidspunkt for vanntilsetning:	10.02
Ansvarlig:	K.L. og R.L. (SINTEF)
Utført av:	K.L., R.L. og S.R. (SINTEF)

Materialer	**Resept** kg/m³	**Sats** kg	**Fukt*** %	**Korr.** kg	**Oppveid**** kg	
Norcem Standard FA	438,2	13,147			13,147	
	0,0	0,000			0,000	
	0,0	0,000			0,000	
Elkem Microsilica	43,3	1,300	0,0	0,000	1,300	
0	0,0	0,000			0,000	
	0,0	0,000			0,000	
Fritt vann	220,5	6,614		-1,686	4,928	4,989
Absorbert vann	2,0	0,061			0,061	
Årdal 0/8 naturlig	0,0	0,000	0,0	0,000	0,000	
Årdal 4/8mm naturlig	170,4	5,113	0,6	0,031	5,143	
Ulriken 0/4mm vasket	1536,8	46,105	3,4	1,568	47,672	
Ulriken 0/4mm uvasket	0,0	0,000	0,0	0,000	0,000	
Follob. 0/8mm vasket	0,0	0,000	0,0	0,000	0,000	
Grenseverdier minimum, NB7	0,0	0,000	0,0	0,000	0,000	
Grenseverdier maksimum, NB7	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Sika SSP 2000	3,9	0,116	76	0,088	0,116	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000			0,000	
	0,0	0,000			0,000	

*Se fotnote på delark "Resept"

** NB! Våte mengder, også for silikaslurry

Sammensatt tilslag

Fraksjon	Navn	Densitet [kg/m³]	Abs. fukt [%]	Alk. reakt. Sv[%]	Klorider [%]	Andel volum	Andel vekt	Bruk
I	Årdal 0/8 naturlig	2680	0,3	0,0	0,00	0,000	0,000	ok
II	Årdal 4/8mm naturlig	2670	0,3	0,0	0,00	0,109	0,100	ok
III	Ulriken 0/4mm vasket	2960	0,1	0,0	0,00	0,891	0,900	ok
IV	Ulriken 0/4mm uvasket	2960	0,1	0,0	0,00	0,000	0,000	
V	Follob. 0/8mm vasket	2760	0,2	0,0	0,00	0,000	0,000	
VI	Grenseverdier minimum, NI	2700	0,0	0,0	0,00	0,000	0,000	
VII	Grenseverdier maksimum, N	2700	0,0	0,0	0,00	0,000	0,000	
VIII		2700	0,0	0,0	0,00	0,000	0,000	
IX		2700	0,0	0,0	0,00	0,000	0,000	
X		2700	0,0	0,0	0,00	0,000	0,000	
Sammensatt		2928		0,0	0,00	1,000	1,000	

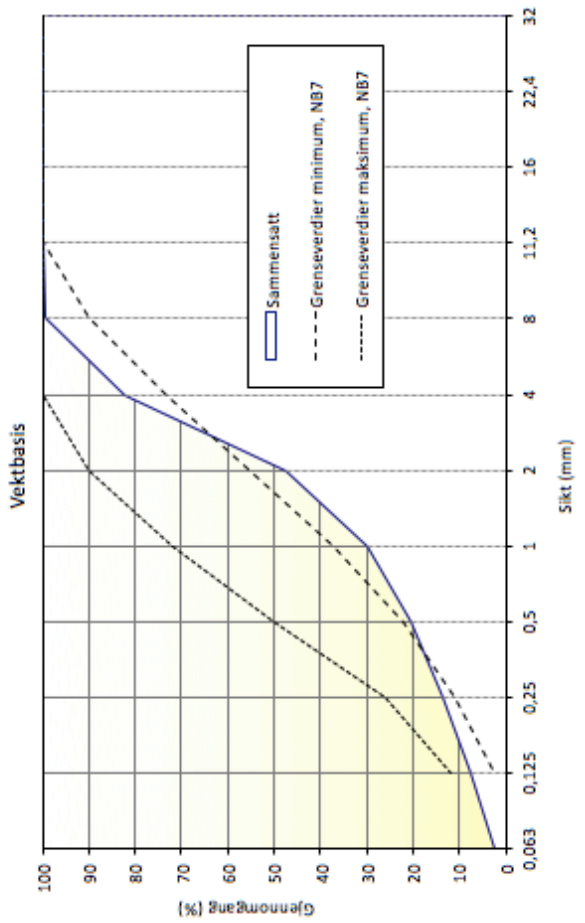
Finhetsmoduler	
FM_{vekt} =	3,53
FM_{vol} =	3,55
FM_{ref} =	3,02
FMg =	5,55

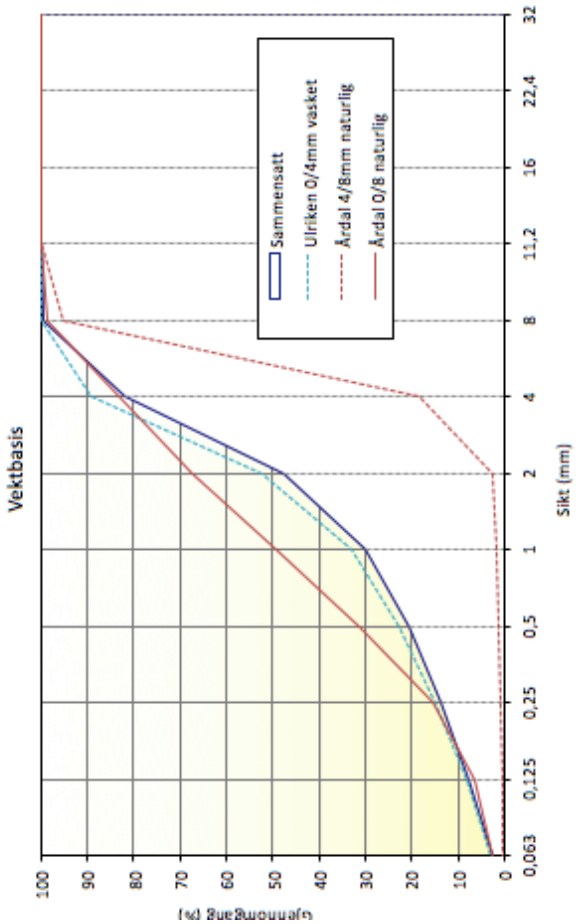
Tilpass til ref. gradering, Ctrl T

Sett ref. gradering, Ctrl R

Tilpass til FMg, Ctrl F

Åpning	Gjennomgang vol.[%]	Gjennomgang vekt [%]	Ref. grad. [vol. %]	Vekt ved tilpasning
32	100,0	100,0	100,0	1
22,4	100,0	100,0	100,0	1
16	100,0	100,0	100,0	1
11,2	100,0	100,0	100,0	1
8	99,5	99,5	98,8	1
4	81,4	82,1	83,3	1
2	47,0	47,5	67,2	1
1	29,6	29,9	49,1	2
0,5	20,2	20,4	31,1	2
0,25	13,4	13,6	15,5	2
0,125	7,4	7,5	6,2	2
0,063	2,5	2,5	2,4	2



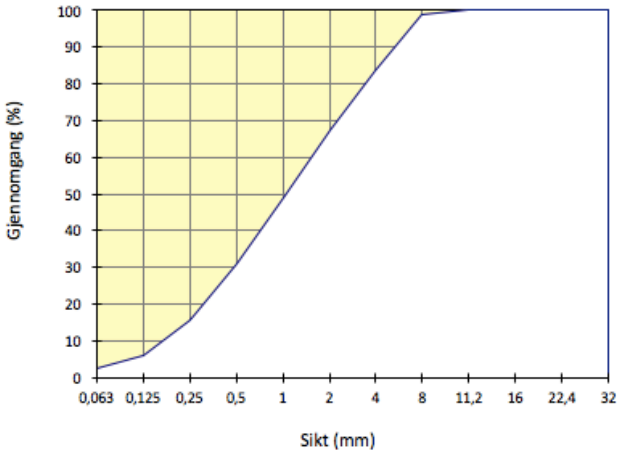


Aggregate grading

Fraksjon I

Type:	Årdal 0/8 naturlig
Dato:	07/02/2017
FM =	3,02

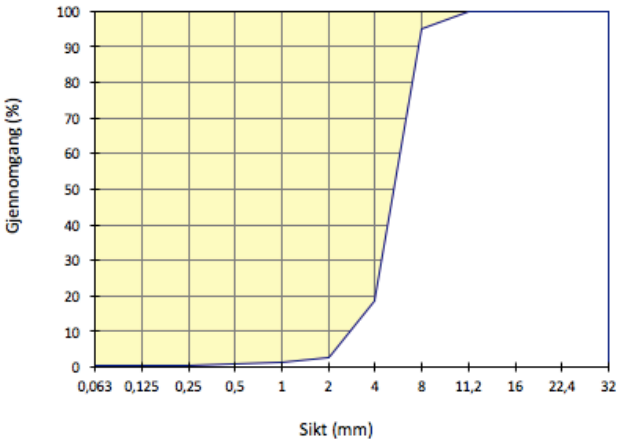
Åpning	Sikterest (g)		Sikterest (%)	Gjennom-gang (%)
	1	2		
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	0	0	0,0	100,0
11,2	0	0	0,0	100,0
8	8,8	8,8	1,2	98,8
4	121,5	121,5	16,7	83,3
2	239	239	32,8	67,2
1	371,4	371,4	50,9	49,1
0,5	502,8	502,8	68,9	31,1
0,25	616,3	616,3	84,5	15,5
0,125	684,7	684,7	93,8	6,2
0,063	712,1	712,1	97,6	2,4
Bunn	730	730		



Fraksjon II

Type:	Årdal 4/8mm naturlig
Dato:	07/02/2017
FM =	5,30

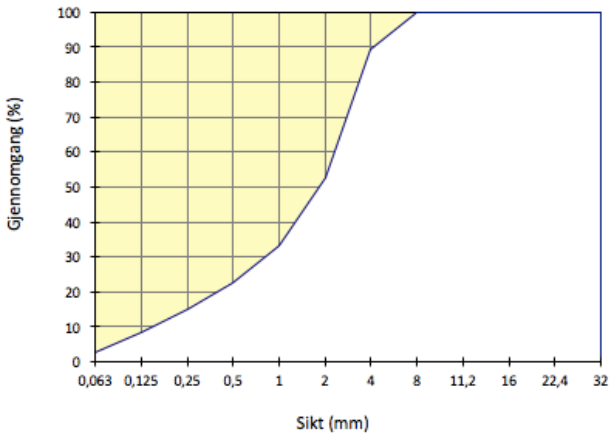
Åpning	Sikterest (g)		Sikterest (%)	Gjennom-gang (%)
	1	2		
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	0	0	0,0	100,0
11,2	0	0	0,0	100,0
8	4,8	4,8	4,8	95,2
4	81,6	81,6	81,6	18,4
2	97,4	97,4	97,4	2,6
1	98,5	98,5	98,5	1,5
0,5	98,9	98,9	98,9	1,1
0,25	99,3	99,3	99,3	0,7
0,125	100	100	99,6	0,4
0,063	100	100	99,7	0,3
Bunn	100	100		



Fraksjon III

Type:	Ulriken 0/4mm vasket
Dato:	07/02/2017
FM =	3,34

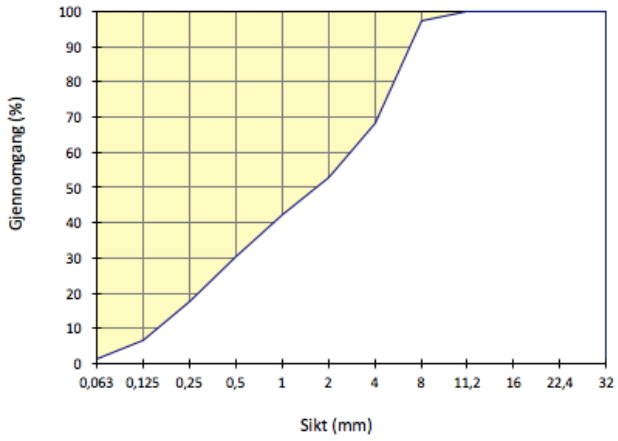
Åpning	Sikterest (g)		Sikterest	Gjennom-gang
	1	2	(%)	(%)
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	0	0	0,0	100,0
11,2	0	0	0,0	100,0
8	0	0	0,0	100,0
4	114	114	10,8	89,2
2	503	503	47,6	52,4
1	708	708	66,9	33,1
0,5	820	820	77,4	22,6
0,25	900	900	85,0	15,0
0,125	971	971	91,8	8,2
0,063	1029	1029	97,2	2,8
Bunn	1059	1059		



Fraksjon V

Type:	Follob. 0/8mm vasket
Dato:	07/02/2017
FM =	3,38

Åpning	Sikterest (g)		Sikterest	Gjennom-gang
	1	2	(%)	(%)
32	0	0	0,0	100,0
22,4	0	0	0,0	100,0
16	0	0	0,0	100,0
11,2	0	0	0,0	100,0
8	25,8	25,8	2,7	97,3
4	307	307	31,9	68,1
2	454,1	454,1	47,2	52,8
1	554,9	554,9	57,6	42,4
0,5	668,5	668,5	69,4	30,6
0,25	793,3	793,3	82,4	17,6
0,125	896,9	896,9	93,2	6,8
0,063	948	948	98,5	1,5
Bunn	963	963		



Appendix A.3 – Excel spreadsheet used to prepare the test samples for the void content test (page 1) and to calculate the void content of each particle phase composition (page 2)

Measurement series no.	Composition no.*	Weight fraction [-] **			Weight [g]**			Quantity to be added [g]**			Total weight [g]
		MR1	MU1	MR2	MR1	MU1	MR2	MR1	MU1	MR2	
1	1	1.00	0.00	0.00	8843	0	0	0	0	0	8843
2	2	0.90	0.09	0.01	8843	884	98	0	884	98	9826
3	3	0.80	0.18	0.02	8843	1990	221	0	1105	123	11054
4	4	0.70	0.27	0.03	8843	3411	379	0	1421	158	12633
5	5	0.60	0.36	0.04	8843	5306	590	0	1895	211	14738 (S)
6	6 (1)	0.50	0.45	0.05	8843	7959	884	0	2653	295	17686 (S)
7	11	0.00	0.90	0.10	0	850	7650	0	0	0	8500
8	10	0.10	0.81	0.09	944	850	7650	944	0	0	9444
9	9	0.20	0.72	0.08	2125	850	7650	1181	0	0	10625
10	8	0.30	0.63	0.07	3643	850	7650	1518	0	0	12143
11	7	0.40	0.54	0.06	5667	850	7650	2024	0	0	14167 (S)
12	6 (2)	0.50	0.45	0.05	8500	850	7650	2833	0	0	17000 (S)

Measurement series no.	Composition no.*	Weight fraction [-] **		Weight [g]**		Quantity to be added [g]**		Total weight [g]
		MR1	MF	MR1	MF	MR1	MF	
13	12	1.00	0.00	8278	0	0	0	8278
14	13	0.90	0.10	8278	920	0	920	9198
15	14	0.80	0.20	8278	2070	0	1150	10348
16	15	0.70	0.30	8278	3548	0	1478	11826
17	16	0.60	0.40	8278	5519	0	1971	13797 (S)
18	17 (1)	0.50	0.50	8278	8278	0	2759	16556 (S)
19	22	0.00	1.00	0	8164	0	0	8164
20	21	0.10	0.90	907	8164	907	0	9071
21	20	0.20	0.80	2041	8164	1134	0	10205
22	19	0.30	0.70	3499	8164	1458	0	11663
23	18	0.40	0.60	5443	8164	1944	0	13607 (S)
24	17 (2)	0.50	0.50	8164	8164	2721	0	16328 (S)

General information	
Volume of the container	4.9 l
Weight of the container	1312 g
Density of aggregate	
MR1	2.68 Mg/m3
MR2	2.67 Mg/m3
MU1	2.96 Mg/m3
MF	2.76 Mg/m3
Estimated quantity needed to fill the container (assuming packing = 0.7)	
MR1	9755 g
MU1 + MR2	10669 g
MF	10046 g

* According to Table 3.7
** Referring to particles > 0.125 mm
(S) Sample was reduced with splitting

Appendix A.3

Excel spreadsheet used to prepare the test samples for the void content test (page 1) and to calculate the void content of each particle phase composition (page 2)

Measurement series no.	Composition no.*	Weight fraction [-]**			Weight [g]				Bulk density [Mg/m3]				Particle density [Mg/m3]					Void content [%]
		MR1	MU1	MR2	Sample 1	Sample 2	Sample 3	Sample 4	Sample 1	Sample 2	Sample 3	Sample 4	Average value	Sample 1	Sample 2	Sample 3	Sample 4	Average value
1	1	1.00	0.00	0.00	9561.0	9668.1	9617.3		1.67	1.69	1.68		2.68	37.79	36.99	37.37		37.38
2	2	0.90	0.09	0.01	9560.0	9630.0	9560.0		1.67	1.68	1.67		2.71	38.38	37.86	38.38		38.20
3	3	0.80	0.18	0.02	9543.0	9528.0	9536.0		1.66	1.66	1.66		2.73	39.07	39.18	39.12		39.13
4	4	0.70	0.27	0.03	9506.0	9645.0	9610.0		1.66	1.68	1.68		2.76	39.90	38.88	39.13		39.30
5	5	0.60	0.36	0.04	9517.0	9491.0	9555.0		1.66	1.65	1.67		2.78	40.36	40.55	40.08		40.33
6	6 (1)	0.50	0.45	0.05	9522.0	9458.0	9564.0		1.66	1.65	1.67		2.81	40.86	41.32	40.56		40.91
7	11	0.00	0.90	0.10	9193.6	9219.9	9221.6		1.59	1.60	1.60		2.93	45.65	45.47	45.46		45.53
8	10	0.10	0.81	0.09	9288.4	9323.9	9361.4		1.61	1.62	1.63		2.91	44.53	44.28	44.02		44.27
9	9	0.20	0.72	0.08	9297.8	9444.2	9386.2		1.61	1.64	1.63		2.88	43.98	42.95	43.36		43.43
10	8	0.30	0.63	0.07	9487.5	9528.3	9470.5		1.65	1.66	1.65		2.86	42.14	41.85	42.26		42.09
11	7	0.40	0.54	0.06	9480.9	9519.5	9464.8		1.65	1.66	1.65		2.83	41.68	41.40	41.79		41.62
12	6 (2)	0.50	0.45	0.05	9518.4	9567.5	9592.0		1.66	1.67	1.67		2.81	40.88	40.53	40.35		40.59

Measurement series no.	Composition no.*	Weight fraction [-] **		Weight [g]				Bulk density [Mg/m3]					Particle density [Mg/m3]					Void content [%]
		MR1	MF	Sample 1	Sample 2	Sample 3	Sample 4	Sample 1	Sample 2	Sample 3	Sample 4		Average value	Sample 1	Sample 2	Sample 3	Sample 4	Average value
13	12	1.00	0.00	9589.1	9557.6	9574.3		1.67	1.67	1.67			2.68	37.58	37.82	37.69		37.70
14	13	0.90	0.10	9514.4	9682.4	9576.4		1.66	1.69	1.67			2.69	38.33	37.07	37.86		37.75
15	14	0.80	0.20	9536.7	9593.6	9606.4		1.66	1.67	1.68			2.70	38.35	37.92	37.82		38.03
16	15	0.70	0.30	9524.1	9580.2	9560.1		1.66	1.67	1.67			2.70	38.62	38.20	38.35		38.39
17	16	0.60	0.40	9484	9591	9572.6		1.65	1.67	1.67			2.71	39.10	38.30	38.44		38.62
18	17 (1)	0.50	0.50	9475.6	9455.1	9445.1		1.65	1.65	1.64			2.72	39.34	39.50	39.57		39.47
19	22	0.00	1.00	2928.2	2881.2	2927.6	9476.2	1.64	1.61	1.64	1.65		2.76	40.47	41.58	40.48	40.22	40.69
20	21	0.10	0.90	9452.2	9370.6	9443.2		1.65	1.63	1.64			2.75	40.22	40.82	40.29		40.44
21	20	0.20	0.80	9439.8	9473.9	9540.7		1.64	1.65	1.66			2.74	40.14	39.89	39.39		39.81
22	19	0.30	0.70	9514.4	9434.3	9507.5		1.66	1.64	1.66			2.74	39.41	40.00	39.46		39.63
23	18	0.40	0.60	9429	9466.3	9484.5		1.64	1.65	1.65			2.73	39.87	39.59	39.46		39.64
24	17 (2)	0.50	0.50	9337.4	9499.8	9353.4		1.62	1.65	1.63			2.72	40.37	39.16	40.25		39.93

Orange cells: An error with the orginal test samples was dicsovered afterwards and the error was corrected with new test samples. These samples were tested with a smaller container due to lack of materials. The container had a weight of 423.8 g and a volume of 1.5 l.

Appendix A.4 – The composition of the mixes in the FlowCyl test series

Mix $U1_I$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2060.9	0.69	3000
Silica fume	203.8	0.09	2200
Free water	1028.1	1.03	1000
Absorbed water	0.0	0.00	1000
Fines MU1	279.8	0.09	2960
Fines MR1	233.7	0.09	2680
Fines MR2	0.0	0.00	2670
Superplasticizer (0.5 % of binder content)	11.2	0.01	1055
Sum	3817.4	2.00	1908.7

Total fines content	513.5	g
Fines/binder ratio	0.23	
Fraction MU1	54.5	%
Fraction MR1	45.5	%
Fraction MR2	0.0	%

Mix $U2_I$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2059.6	0.69	3000
Silica fume	203.7	0.09	2200
Free water	1023.3	1.02	1000
Absorbed water	0.0	0.00	1000
Fines MU1	279.7	0.09	2960
Fines MR1	233.7	0.09	2680
Fines MR2	0.0	0.00	2670
Superplasticizer (0.75 % of binder content)	16.7	0.02	1055
Sum	3816.8	2.00	1908.4

Total fines content	513.4	g
Fines/binder ratio	0.23	
Fraction MU1	54.5	%
Fraction MR1	45.5	%
Fraction MR2	0.0	%

Mix $U3_I$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2058.1	0.69	3000
Silica fume	203.7	0.09	2200
Free water	1018.1	1.02	1000
Absorbed water	0.0	0.00	1000
Fines MU1	279.7	0.09	2960
Fines MR1	233.7	0.09	2680
Fines MR2	0.0	0.00	2670
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	3816.0	2.00	1908.0

Total fines content	513.4	g
Fines/binder ratio	0.23	
Fraction MU1	54.5	%
Fraction MR1	45.5	%
Fraction MR2	0.0	%

Mix $U4_I$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2055.9	0.69	3000
Silica fume	203.3	0.09	2200
Free water	1008.4	1.01	1000
Absorbed water	0.0	0.00	1000
Fines MU1	279.7	0.09	2960
Fines MR1	233.7	0.09	2680
Fines MR2	0.0	0.00	2670
Superplasticizer (1.5 % of binder content)	34.0	0.03	1055
Sum	3815.0	2.00	1907.5

Total fines content	513.4	g
Fines/binder ratio	0.23	
Fraction MU1	54.5	%
Fraction MR1	45.5	%
Fraction MR2	0.0	%

Mix $F1_l$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2069.2	0.69	3000
Silica fume	204.7	0.09	2200
Free water	1032.3	1.03	1000
Absorbed water	0.0	0.00	1000
Fines MF	249.4	0.09	2760
Fines MR1	225.1	0.08	2680
Superplasticizer (0.5 % of binder content)	11.2	0.01	1055
Sum	3791.9	2.00	1895.9
Total fines content	474.5	g	
Fines/binder ratio	0.21		
Fraction MF	52.6	%	
Fraction MR1	47.4	%	

Mix $F2_l$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2067.5	0.69	3000
Silica fume	204.6	0.09	2200
Free water	1027.2	1.03	1000
Absorbed water	0.0	0.00	1000
Fines MF	249.3	0.09	2760
Fines MR1	225.1	0.08	2680
Superplasticizer (0.75 % of binder content)	17.2	0.02	1055
Sum	3790.9	2.00	1895.4
Total fines content	474.4	g	
Fines/binder ratio	0.21		
Fraction MF	52.6	%	
Fraction MR1	47.4	%	

Mix $F3_I$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2066.6	0.69	3000
Silica fume	204.2	0.09	2200
Free water	1022.4	1.02	1000
Absorbed water	0.0	0.00	1000
Fines MF	249.4	0.09	2760
Fines MR1	225.1	0.08	2680
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	3790.4	2.00	1895.2
Total fines content	474.5	g	
Fines/binder ratio	0.21		
Fraction MF	52.6	%	
Fraction MR1	47.4	%	

Mix $F4_I$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2064.2	0.69	3000
Silica fume	204.2	0.09	2200
Free water	1012.6	1.01	1000
Absorbed water	0.0	0.00	1000
Fines MF	249.4	0.09	2760
Fines MR1	225.1	0.08	2680
Superplasticizer (1.5 % of binder content)	34.0	0.03	1055
Sum	3789.4	2.00	1894.7
Total fines content	474.5	g	
Fines/binder ratio	0.21		
Fraction MF	52.6	%	
Fraction MR1	47.4	%	

Mix $R1_I$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2079.1	0.69	3000
Silica fume	205.5	0.09	2200
Free water	1037.5	1.04	1000
Absorbed water	0.0	0.00	1000
Fines MR1	442.3	0.17	2680
Superplasticizer (0.5 % of binder content)	11.6	0.01	1055
Sum	3776.1	2.00	1888.0

Total fines content	442.3	g
Fines/binder ratio	0.19	
Fraction MR1	100	%

Mix $R2_I$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2078.0	0.69	3000
Silica fume	205.6	0.09	2200
Free water	1032.5	1.03	1000
Absorbed water	0.0	0.00	1000
Fines MR1	442.4	0.17	2680
Superplasticizer (0.75 % of binder content)	17.2	0.02	1055
Sum	3775.7	2.00	1887.8

Total fines content	442.4	g
Fines/binder ratio	0.19	
Fraction MR1	100	%

Mix $R3_I$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2077.2	0.69	3000
Silica fume	205.6	0.09	2200
Free water	1027.5	1.03	1000
Absorbed water	0.0	0.00	1000
Fines MR1	442.4	0.17	2680
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	3775.5	2.00	1887.7
Total fines content	442.4	g	
Fines/binder ratio	0.19		
Fraction MR1	100	%	

Mix $R4_I$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2074.3	0.69	3000
Silica fume	205.1	0.09	2200
Free water	1017.6	1.02	1000
Absorbed water	0.0	0.00	1000
Fines MR1	442.4	0.17	2680
Superplasticizer (1.5 % of binder content)	34.4	0.03	1055
Sum	3773.9	2.00	1886.9
Total fines content	442.4	g	
Fines/binder ratio	0.19		
Fraction MR1	100	%	

Mix $U1_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2038.6	0.68	3000
Silica fume	201.5	0.09	2200
Free water	1008.6	1.01	1000
Absorbed water	0.0	0.00	1000
Fines MU1	211.0	0.07	2960
Superplasticizer (1.0 % of binder content)	22.3	0.02	1055
Sum	3482.1	1.87	1859.9
Total fines content	211.0	g	
Fines/binder ratio	0.10		
Fraction MU1	100	%	

Mix $U2_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2038.6	0.68	3000
Silica fume	201.5	0.09	2200
Free water	1008.6	1.01	1000
Absorbed water	0.0	0.00	1000
Fines MU1	453.7	0.15	2960
Superplasticizer (1.0 % of binder content)	22.3	0.02	1055
Sum	3724.8	1.95	1906.0
Total fines content	453.7	g	
Fines/binder ratio	0.22		
Fraction MU1	100	%	

Mix $U3_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2038.6	0.68	3000
Silica fume	201.5	0.09	2200
Free water	1008.6	1.01	1000
Absorbed water	0.0	0.00	1000
Fines MU1	680.5	0.23	2960
Superplasticizer (1.0 % of binder content)	22.3	0.02	1055
Sum	3951.7	2.03	1945.8
Total fines content	680.5	g	
Fines/binder ratio	0.33		
Fraction MU1	100	%	

Mix $U4_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2038.6	0.68	3000
Silica fume	201.5	0.09	2200
Free water	1008.6	1.01	1000
Absorbed water	0.0	0.00	1000
Fines MU1	909.1	0.31	2960
Superplasticizer (1.0 % of binder content)	22.3	0.02	1055
Sum	4180.3	2.11	1983.0
Total fines content	909.1	g	
Fines/binder ratio	0.45		
Fraction MU1	100	%	

Mix $F1_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2055.3	0.69	3000
Silica fume	203.2	0.09	2200
Free water	1017.0	1.02	1000
Absorbed water	0.0	0.00	1000
Fines MF	190.0	0.07	2760
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	3488.3	1.88	1850.7
Total fines content	190.0	g	
Fines/binder ratio	0.09		
Fraction MF	100	%	

Mix $F2_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2055.3	0.69	3000
Silica fume	203.2	0.09	2200
Free water	1017.0	1.02	1000
Absorbed water	0.0	0.00	1000
Fines MF	401.1	0.15	2760
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	3699.4	1.96	1886.1
Total fines content	401.1	g	
Fines/binder ratio	0.20		
Fraction MF	100	%	

Mix $F3_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2055.3	0.69	3000
Silica fume	203.2	0.09	2200
Free water	1017.0	1.02	1000
Absorbed water	0.0	0.00	1000
Fines MF	599.1	0.22	2760
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	3897.4	2.03	1917.0
Total fines content	599.1	g	
Fines/binder ratio	0.29		
Fraction MF	100	%	

Mix $F4_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2055.3	0.69	3000
Silica fume	203.2	0.09	2200
Free water	1017.0	1.02	1000
Absorbed water	0.0	0.00	1000
Fines MF	799.6	0.29	2760
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	4097.9	2.11	1946.0
Total fines content	799.6	g	
Fines/binder ratio	0.39		
Fraction MF	100	%	

Mix $R1_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2077.2	0.69	3000
Silica fume	205.6	0.09	2200
Free water	1027.5	1.03	1000
Absorbed water	0.0	0.00	1000
Fines MR1	191.6	0.07	2680
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	3524.6	1.91	1848.8
Total fines content	191.6	g	
Fines/binder ratio	0.09		
Fraction MR1	100	%	

Mix $R2_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2077.2	0.69	3000
Silica fume	205.6	0.09	2200
Free water	1027.5	1.03	1000
Absorbed water	0.0	0.00	1000
Fines MR1	254.4	0.09	2680
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	3587.5	1.93	1858.9
Total fines content	254.4	g	
Fines/binder ratio	0.12		
Fraction MR1	100	%	

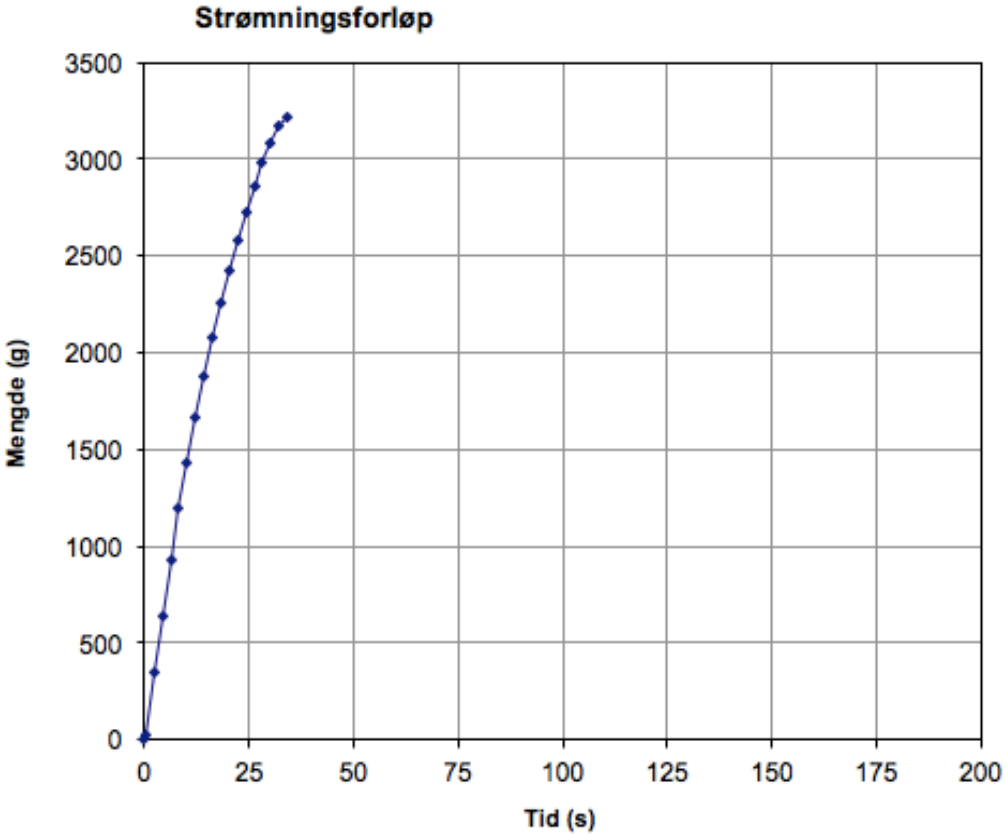
Mix $R3_{II}$

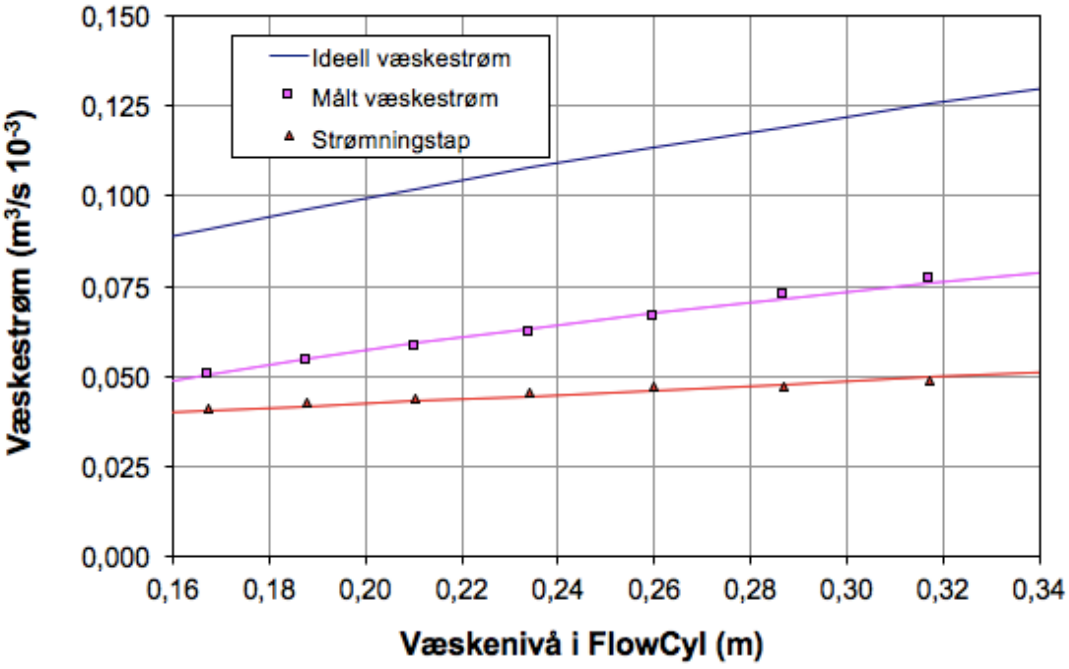
Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2077.2	0.69	3000
Silica fume	205.6	0.09	2200
Free water	1027.5	1.03	1000
Absorbed water	0.0	0.00	1000
Fines MR1	318.5	0.12	2680
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	3651.6	1.95	1869.0
Total fines content	318.5	g	
Fines/binder ratio	0.15		
Fraction MR1	100	%	

Mix $R4_{II}$

Materials	Weight [g]	Volume [l]	Density [kg/m^3]
Cement	2077.2	0.69	3000
Silica fume	205.6	0.09	2200
Free water	1027.5	1.03	1000
Absorbed water	0.0	0.00	1000
Fines MR1	602.3	0.22	2680
Superplasticizer (1.0 % of binder content)	22.8	0.02	1055
Sum	3935.4	2.06	1910.7
Total fines content	602.3	g	
Fines/binder ratio	0.29		
Fraction MR1	100	%	

Appendix A.5 – Example of data recording and calculation of flow resistance





Beregning av λ_Q

Mix MF4 - 1.5% SP

Størrelse	Tallverdi	Enhet
$\Sigma(Q-Q_{t\text{-}reg})^2$	8,14E-06	
a (polynomkonst.)	3,39E-02	
b (polynomkonst.)	4,38E-02	
c (polynomkonst.)	3,23E-02	
Tverrsnittsareal, *A_åpning*	0,000050	m^2
Tverrsnittsareal, *A_syl*	0,005027	m^2
Tidsinkrement, *n*	2	sek
Utløpsdiameter, *du*	0,008	m
Rørdiameter, *dr*	0,08	m
Øvre grense, *fy_gr*	0,35	m
Nedre grense, *tø_gr*	0,14	m
Fyllingsnivå, *fy_nivå*	0,385	m
Tømmingsnivå, *tø_nivå*	0,125	m
Matriksens densitet, *densitet*	1894,7	kg/m^3

Beregn

λ_Q= 0,42

Strømningsforløp

Tid t (s)	Volum V (m^3 10^{-3})	Væskenivå i FlowCyl h (m)	Målt væske-strøm Q_m (m^3/s 10^{-3})	Normalisert væske-strøm $Q_{m\text{-}reg}$ (m^3/s 10^{-3})	Ideell strøm Q_t (m^3/s 10^{-3})	Strømnings-tap Q_t (m^3/s 10^{-3})	Normalisert strømnings-tap $Q_{t\text{-}reg}$ (m^3/s 10^{-3})	$(Q-Q_{t\text{-}reg})^2$
0,0	0,000	-	-	-	-	-	-	-
0,2	0,015	-	-	-	-	-	-	-
2,2	0,184	0,348	0,081	0,080	0,131	0,050	0,052	2,18E-06
4,2	0,340	0,317	0,077	0,076	0,125	0,048	0,050	1,50E-06
6,2	0,492	0,287	0,073	0,072	0,119	0,047	0,048	8,66E-07
8,2	0,630	0,260	0,066	0,067	0,113	0,047	0,046	1,09E-06
10,2	0,758	0,234	0,062	0,063	0,108	0,046	0,044	1,12E-06
12,2	0,878	0,210	0,058	0,059	0,102	0,044	0,043	7,91E-07
14,2	0,991	0,188	0,054	0,055	0,097	0,042	0,042	3,52E-07
16,2	1,095	0,167	0,050	0,050	0,091	0,041	0,041	2,11E-08
18,2	1,192	0,148	0,047	0,046	0,086	0,039	0,040	2,23E-07
20,2	1,281	-	-	-	-	-	-	-
22,2	1,363	-	-	-	-	-	-	-
24,2	1,439	-	-	-	-	-	-	-
26,2	1,511	-	-	-	-	-	-	-
28,2	1,573	-	-	-	-	-	-	-
30,2	1,628	-	-	-	-	-	-	-
32,2	1,675	-	-	-	-	-	-	-
34,2	1,699	-	-	-	-	-	-	-
36,2	-	-	-	-	-	-	-	-
38,2	-	-	-	-	-	-	-	-
40,2	-	-	-	-	-	-	-	-
42,2	-	-	-	-	-	-	-	-
44,2	-	-	-	-	-	-	-	-
46,2	-	-	-	-	-	-	-	-
48,2	-	-	-	-	-	-	-	-
50,2	-	-	-	-	-	-	-	-
52,2	-	-	-	-	-	-	-	-
54,2	-	-	-	-	-	-	-	-
56,2	-	-	-	-	-	-	-	-
58,2	-	-	-	-	-	-	-	-
60,2	-	-	-	-	-	-	-	-
62,2	-	-	-	-	-	-	-	-

Appendix A.6 – KL VSI – Knut Lervik's Visual Separation Index

The following tables are made by Knut Lervik (SINTEF). The tables are aimed at helping the executives to describe the stability of the fresh concrete based on the appearance of the concrete right after mixing (in the mixer) and the slump-flow test (on the flow board). The original tables are in Norwegian. Hence, translation errors may have occurred.

Table 1: Visual assessment of the fresh concrete right after mixing

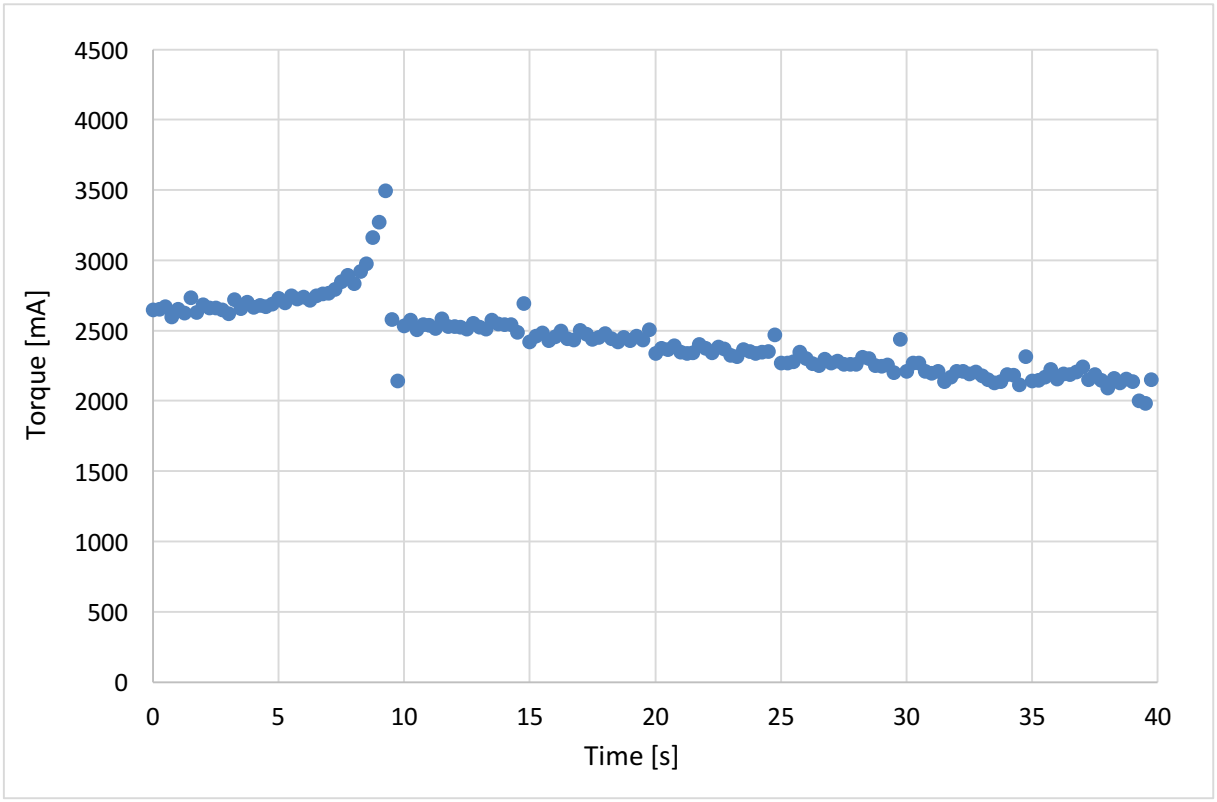
VSI^m	Appearance of the fresh concrete
0 / 0.1	Stable and homogeneous concrete.
0.2 / 0.3	The concrete has a creamy appearance and air voids are visible on the surface, but the concrete is still stable.
0.4 / 0.5	Initial separation. A lot of air voids visible, possible formation of a sludge layer and formation of a dark film on the surface.
0.6 / 0.7	Clear signs of separation. Significant amounts of air voids visible (boiling), formation of a sludge layer and a dark film on the surface, and coarser aggregate particles start to sink and accumulate at the bottom.
0.8 / 0.9	Very prominent signs of separation. Significant amounts of air voids visible (boiling), formation of a water layer on the surface, 5 – 20 mm sludge layer and accumulation of the coarser aggregate particles at the bottom.
1	Completely separation.

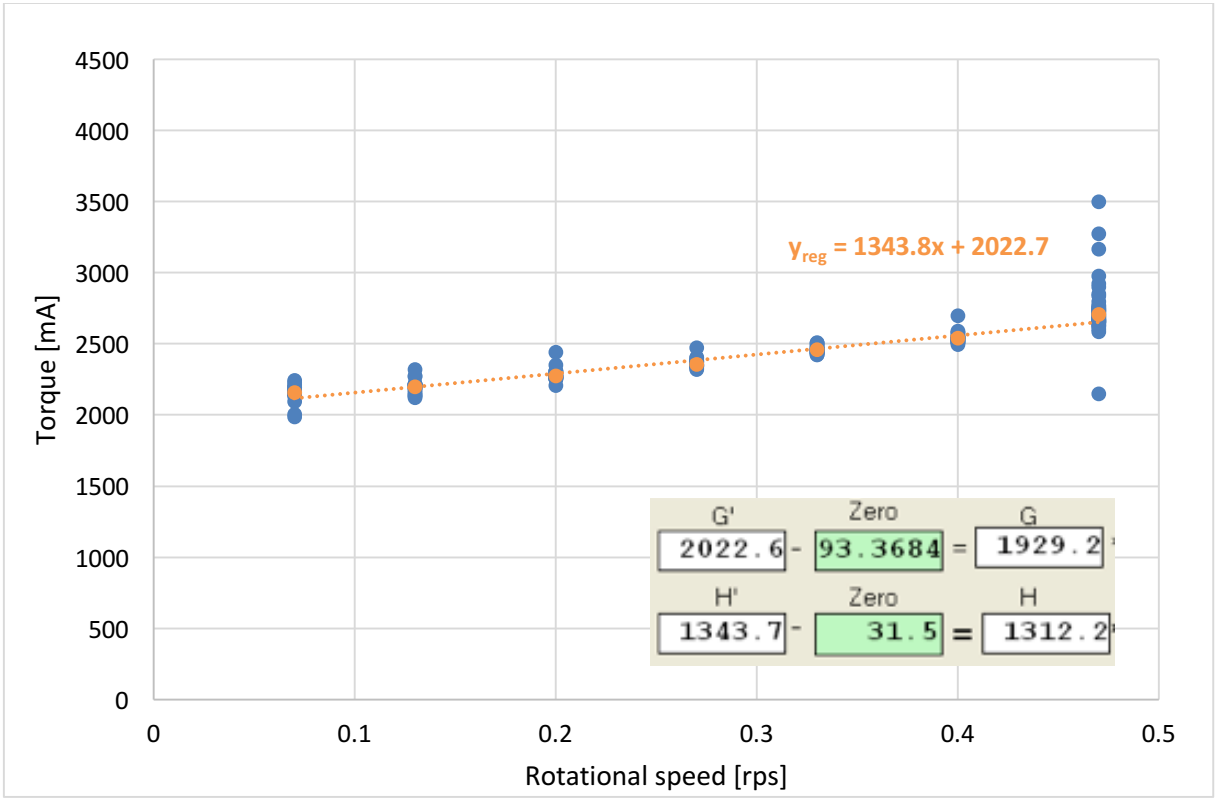
Table 2: Visual assessment of the fresh concrete right after slump-flow test

VSI^f	Appearance of the fresh concrete
0 / 0.1	Stable and homogenous concrete. The concrete flows nicely outwards.
0.2 / 0.3	Stable and homogenous concrete. The concrete flows nicely outwards, but the concrete has a shining appearance with possibly black precipitation particles.
0.4 / 0.5	Stable concrete. The concrete flows nicely outwards, but the concrete has a shining appearance with possibly black precipitation particles. In addition, an outer circumference of flowable cement paste is barely visible.
0.6 / 0.7	Clear outer circumference of flowable cement paste and the coarser aggregate particles tend to be positioned in the centre of the circle.
0.8 / 0.9	Clear outer circumference of flowable cement paste and the coarser aggregate particles tend to be positioned in the centre of the circle. In addition, water separation is visible on the boundary.
1	Completely separation.

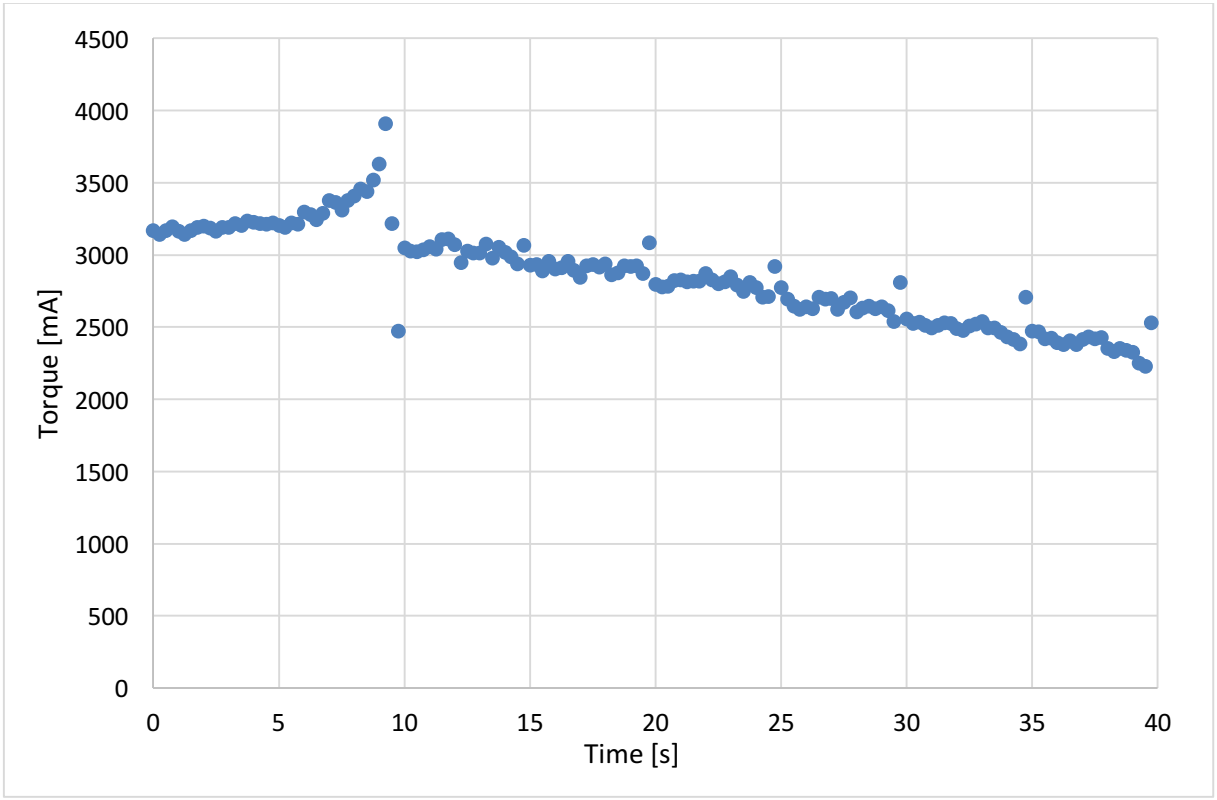
Appendix A.7 – ConTec Rheometer 4SCC raw data and calculation of G and H

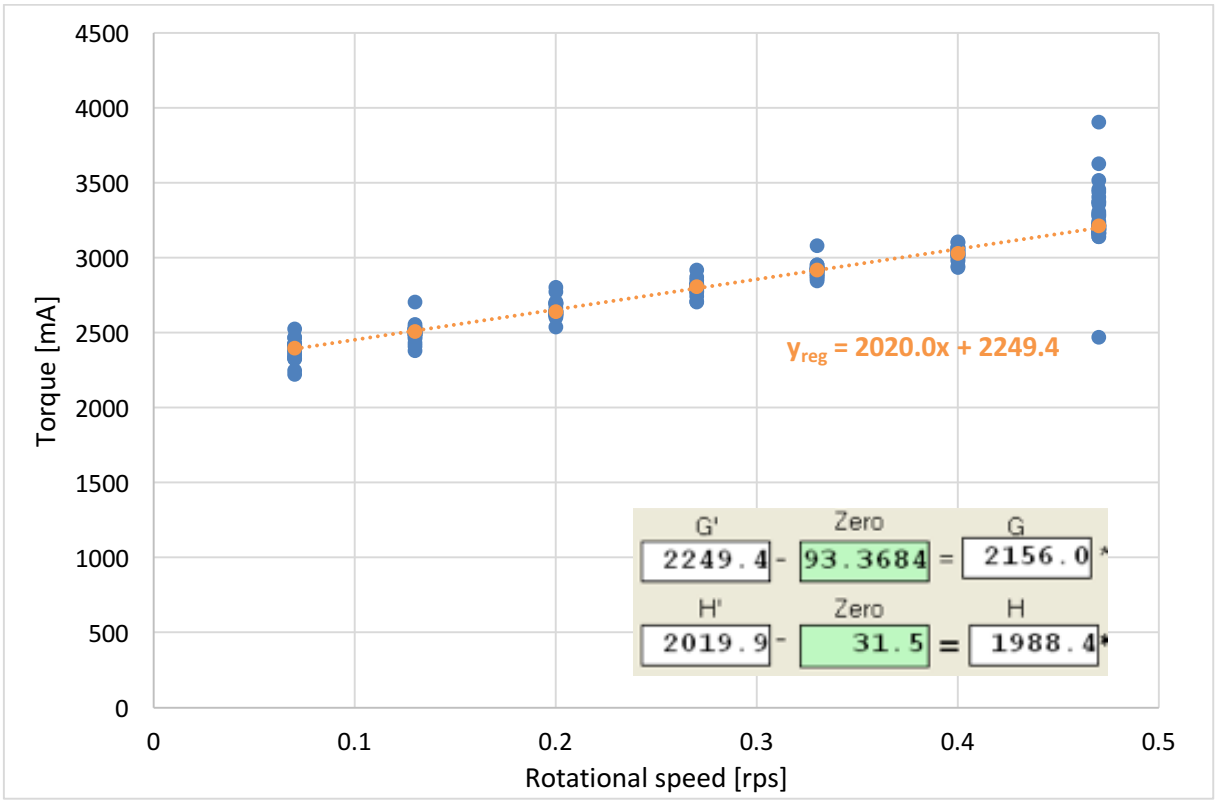
Mix MR100



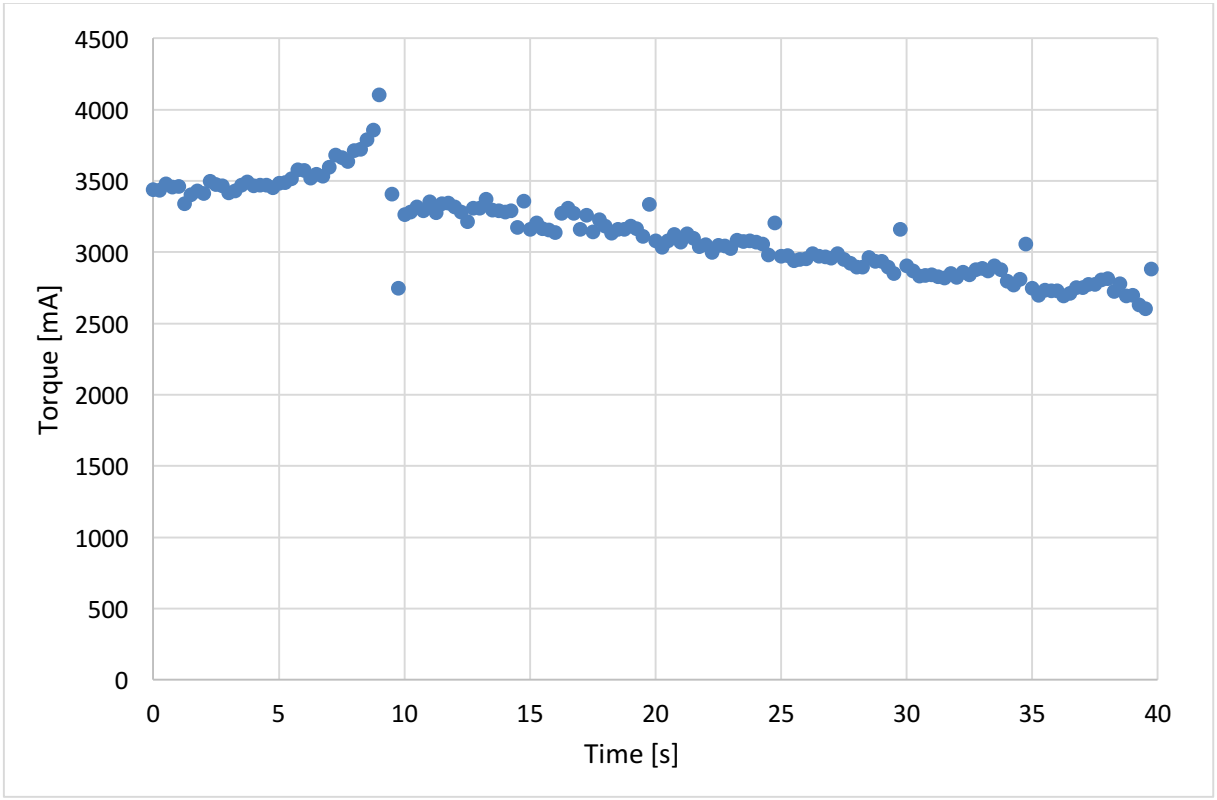


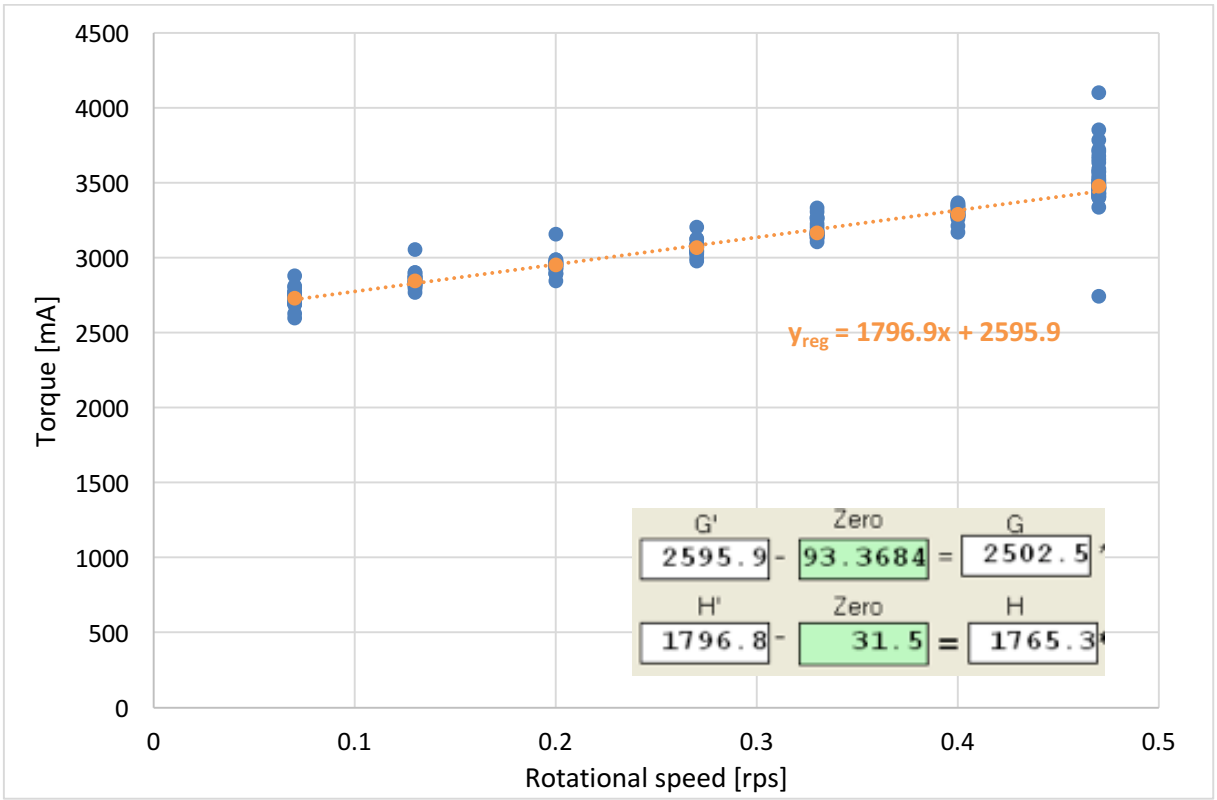
Mix MF50


Torque [mA]
Time [s]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
5
10
15
20
25
30
35
40

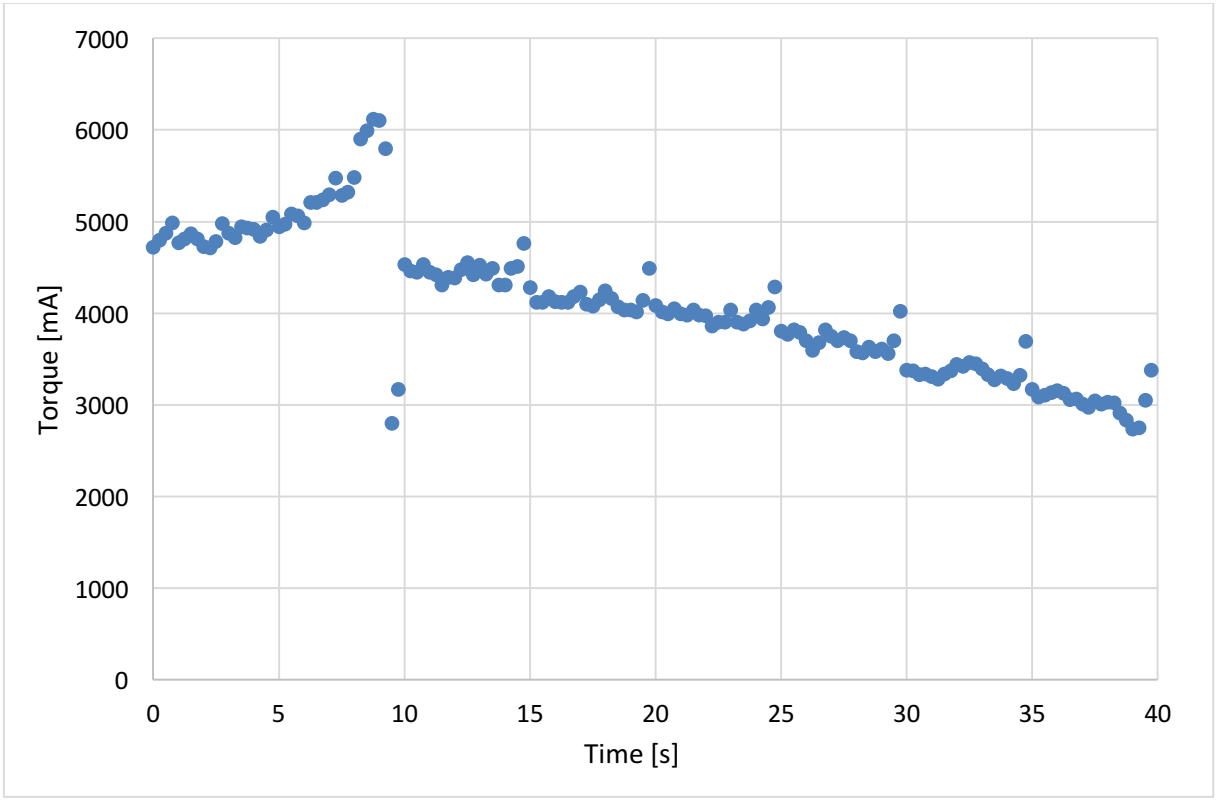

Torque [mA]
Rotational speed [rps]
y_{reg} = 2020.0x + 2249.4
G'
Zero
G
2249.4
93.3684
2156.0
H'
Zero
H
2019.9
31.5
1988.4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
0.1
0.2
0.3
0.4
0.5

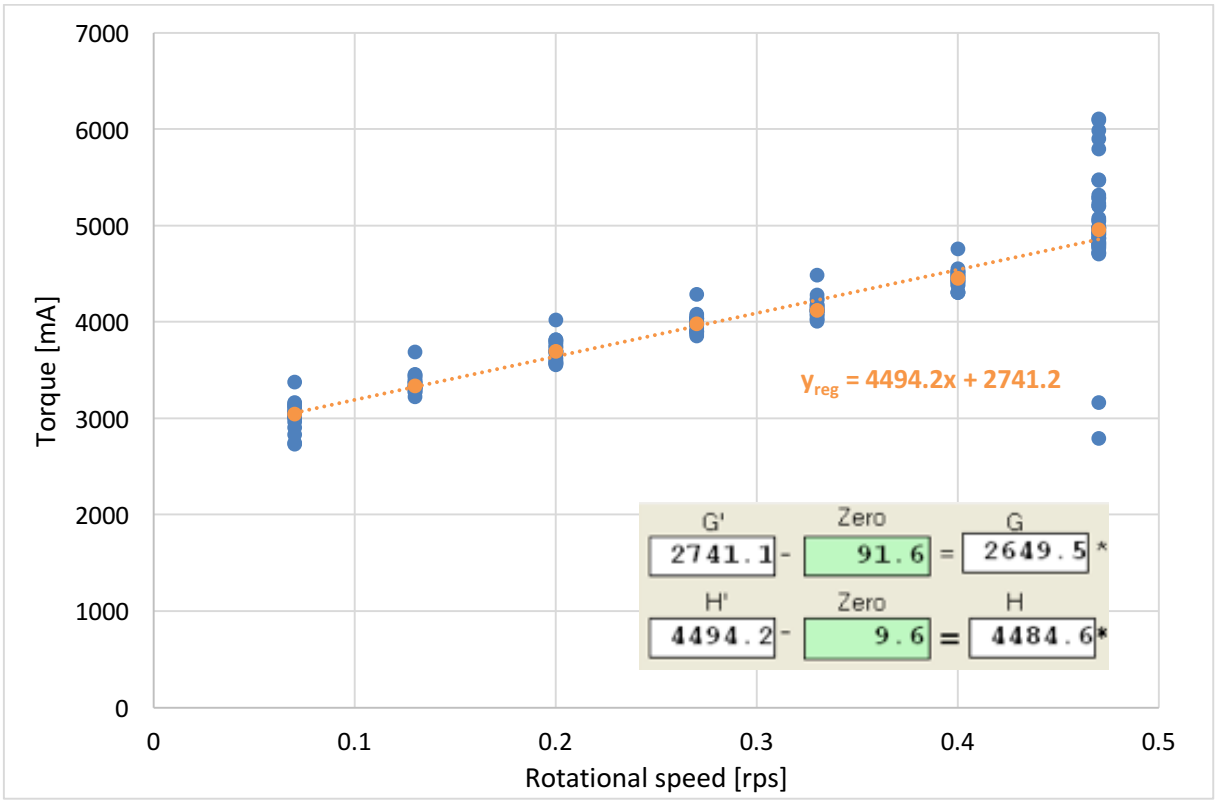
Mix MU50


Torque [mA]
Time [s]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
5
10
15
20
25
30
35
40


Torque [mA]
Rotational speed [rps]
y_{reg} = 1796.9x + 2595.9
G'
Zero
G
2595.9
93.3684
2502.5
H'
Zero
H
1796.8
31.5
1765.3
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
0.1
0.2
0.3
0.4
0.5

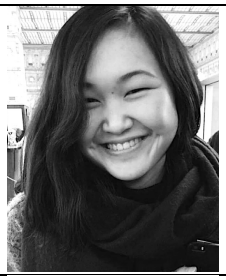
Mix MU100


Torque [mA]
Time [s]
0
1000
2000
3000
4000
5000
6000
7000
0
5
10
15
20
25
30
35
40


Torque [mA]
Rotational speed [rps]
y_{reg} = 4494.2x + 2741.2
G'
Zero
G
2741.1 - 91.6 = 2649.5 *
H'
Zero
H
4494.2 - 9.6 = 4484.6 *
0
1000
2000
3000
4000
5000
6000
7000
0
0.1
0.2
0.3
0.4
0.5

Appendix A.8 – The submitted paper to the XXIIIth Symposium on Nordic Concrete Research and Development

Excavated Rock Materials from Tunnels for Sprayed Concrete

	Judy Luong MSc student Norwegian University of Science and Technology Department of Structural Engineering Richard Birkelandsvei 1a, NO-7491 Trondheim yuenwl@stud.ntnu.no
	Kari Aarstad Siv. Ing., Dr. ing., Senior scientist SINTEF Building, Infrastructure and Architecture Richard Birkelandsvei 3, NO-7465 Trondheim kari.aarstad@sintef.no
	Klaartje De Weerdt MSc, PhD, Associate professor Norwegian University of Science and Technology Department of Structural Engineering Richard Birkelandsvei 1a, NO-7491 Trondheim klaartje.d.weerdt@ntnu.no
	Øyvind Bjøntegaard MSc, PhD, Senior Principal Engineer Norwegian Public Roads Administration Tunnel and Concrete section Abels gate 5, 7030 Trondheim oyvind.bjontegaard@vegvesen.no

ABSTRACT
Sand extracted from natural resources is widely used in concrete production nowadays. The increase in demand for concrete production has resulted in shortage of natural sand resources, especially in terms of suitable materials for concrete production. At the same time, large amounts of excavated rock materials are and have been generated from tunnelling projects and discarded. Hence, there is an opportunity to use these excavated rock materials as aggregates for concrete production. The challenge lays in the production of suitable aggregates. The focus of the study presented in this paper is on the use of processed excavated rock materials from tunnelling projects as aggregates in sprayed concrete production. Five sand materials, both natural and excavated, have been characterized. The effect of three of these materials' properties on the workability properties of the resulting spray concrete will be investigated. The study is not completed yet and a final conclusion remains to be drawn.

Key words: Aggregate, Mix Design, Reuse and Recycling, Rheology, Sustainability

1 INTRODUCTION

High amounts of excavated rock materials are produced in infrastructure projects in Norway, especially when tunnelling is involved. In 2015, 7 million m^3 rock material was excavated from Norwegian mountains [1]. Most of this material has traditionally been used as landfill or placed in deposits in lakes or fjords. However, this practice is becoming more and more controversial, and the project *Local Materials* (Kortreist stein) was established to accommodate extended use of this material. Four areas of possible utilization have been identified in this project: Asphalt, concrete, road construction and ballast, sub- and super structures in railway. This paper is limited to the study of the utilization of excavated rock materials in sprayed concrete production as tunnelling projects often require high volumes of sprayed concrete. Utilizing the excavated rock materials in this manner may be both economically, logistically and environmentally beneficial.

2 MATERIALS AND METHODS

2.1 Materials

In total five different types of sand materials from three different sources have been included in the study. The most essential information about these materials is summarized in Table 1. Three of these sand materials are processed excavated rock materials from two ongoing tunnelling projects in Norway, the new Ulriken tunnel and the Follo Line tunnel. The Follo Line connects Oslo and Ski with a 20 km long double track railway tunnel, and the Ulriken tunnel is an 8 km long double track railway tunnel between Bergen and Arna. Both tunnels are mainly driven by Tunnel boring machines (TBM), but the method drill&blast (D&B) is also applied. Furthermore, the natural sand materials from Årdal (Norstone AS) have been included in the study as reference materials for comparison with the crushed sand materials.

Table 1 - Description of the sand materials used in the study.

Name	Source	Particle sizes	Type of aggregate	Production process		Rock types
				Main process	Secondary process	
MR1	Årdal	0 – 8 mm	Natural	Glaciofluvial and moraine deposit	Partly crushed Washed	Dark rocks Granite/gneiss Feldspathic rocks
MR2	Årdal	4 – 8 mm	Natural	Glaciofluvial and moraine deposit	Partly crushed Washed	Dark rocks Granite/gneiss Feldspathic rocks
MU1	Ulriken	0 – 4 mm	Crushed	Tunnelling D&B	Crushed Washed	Dark rocks Granite/gneiss Feldspathic rocks
MU2	Ulriken	0 – 4 mm	Crushed	Tunnelling D&B	Crushed	Dark rocks Granite/gneiss Feldspathic rocks
MF	Follo-banen	0 – 8 mm	Crushed	Tunnelling TBM	Crushed Washed	Granite/gneiss

The natural sand materials from Årdal, MR1 and MR2, are partly processed in terms of crushing of particles greater than 22 mm and washing [2]. The sand materials from Ulriken, MU1 and MU2, are crushed from the larger rock fragments that are produced during the traditional tunnelling method drill&blast. The crushing process includes a jaw crusher, a gyratory crusher and a cone crusher [3]. The sand material from Follo Line is produced by crushing TBM muck into smaller particles [4]. The crushing includes a cone crusher and a Vertical Shaft Impacter (VSI).

2.2 Experimental program

Characterization

Only the properties that are considered as relevant have been declared and included in the study. These properties are grading, fines content, particle density and water absorption, particle shape and free mica content.

Mix design

Sprayed concrete mix design from a commercial ready-mix concrete supplier has been used as basis for the proportioning part. Three mixes have been proportioned: one mix containing 50% MR1, 45 % MU1 and 5 % MR2, one mix containing 50 % MF and 50 % MR1 and finally one reference mix containing 100 % MR1. MU1 and MR2 were combined to form one unit, containing particles with sizes in the entire range of interest (0 – 8 mm). MU2 is excluded in the study of fresh concrete properties due to its high content of fines (see Table 2), which is known to have a negative impact on workability properties.

FlowCyl test and void content measurement

The FlowCyl test and the void content measurements are based on the particle-matrix model [5]. In the particle-matrix model, fresh concrete is considered as a two-phase system, consisting of a flowable part, the *matrix phase*, and a friction part, the *particle phase*. The FlowCyl test and the void content measurements will and have been carried out in order to characterize the properties of the matrix phase and the particle phase, respectively. According to the particle-matrix model, the workability of fresh concrete is determined by the properties of the phases and the volume ratio between them. Hence, the results of these experiments can give an indication of the workability properties of the sprayed concrete mixes, such that any necessary adjustments and changes on the proportioning part can be made before conducting the remaining experiments.

Fresh concrete properties measurements

Testing of fresh concrete properties by means of slump test, flow-table test and 4SCC have not been performed yet. These experiments will be carried out during Spring 2017.

3 RESULTS AND DISCUSSION

The results of the characterization and the particle void content measurements are presented in Table 2 and Figure 1. The results confirm that the use of VSI in the crushing process provides higher particle shape quality and that the crushing process generally will generate a lot of fines and shall therefore be combined with a wet- or air classification step in order to keep the fines content within acceptable limits.

In general, low content of flaky and elongated particles, low free mica content and low particle void content is beneficial for the workability properties. As expected, Table 2 shows that MR1 has the highest particle shape quality, whereas MU1 and MU2 have the poorest. Consequently, the particle void content is higher in the combined sand material MR1/MF than the other combined sand material MR1/MU1/MR2 (see Figure 1). The combinations are presented as the quantity of crushed sand, specifically MF and MU1 + MR2 in percentage of total mass. MF has the highest content of free mica. This can be related to the application of VSI in the crushing process, which generally generate high amounts of fine particles. When dealing with rock types containing mica, the use of VSI may also cause high content of free mica minerals. In overall, MF seems to be a more suitable aggregate in concrete production than MU1. A final conclusion remains to be drawn after the fresh concrete mixes are tested.

Table 2 - Characterized properties for the sand materials.

	MR1	MR2	MU1	MU2	MF
Fines content	3,0 %	0,5 %	2,7 %	14,0 %	1,5 %
Particle density	2,68 Mg/m^3	2,67 Mg/m^3	2,96 Mg/m^3	2,96 Mg/m^3[a)]	2,76 Mg/m^3
Water adsorpt.	0,3 %	0,5 %	0,1 %	0,1 %[a)]	0,2 %
Particle shape[b)]	25 % / 20 %	-	70 % / 55 %	70 % / 55 %[a)]	40 % / 25 %
Mica content	4 %	-	11 %	11 %[a)]	24 %

[a)] The value for MU2 is assumed to be the same as the value for MU1.
[b)] The values indicate the percentage of flaky/elongated particles. The first value is related to the 2 – 4 mm particles, whereas the second value is related to the 4 – 8 mm particles.
"-" Not declared

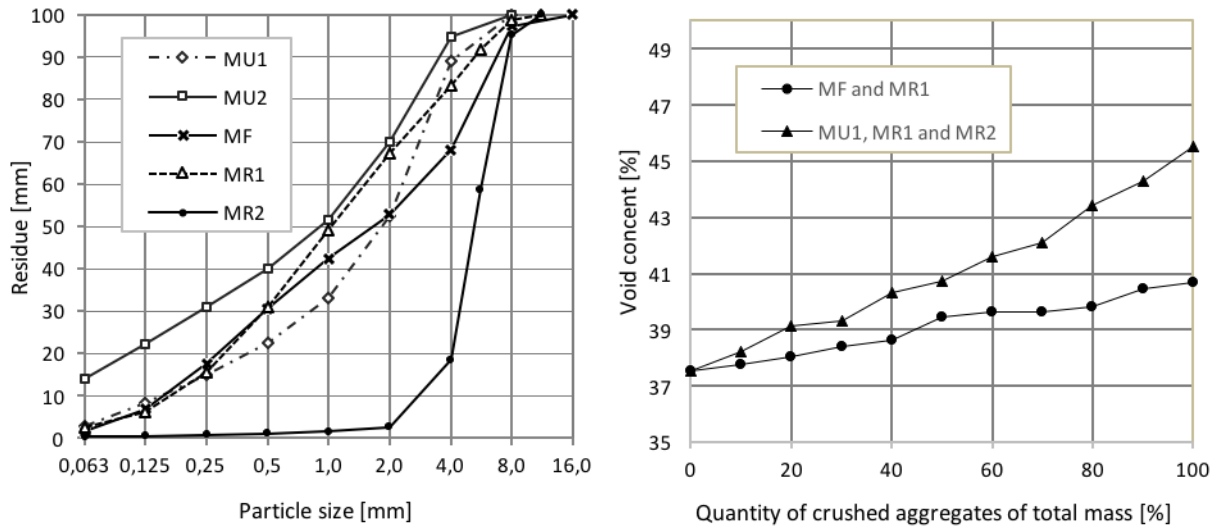


Figure 1 - Sieve curves (left) and void content (right) for the investigated sand materials.

ACKNOWLEDGEMENT

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