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Micro Proportioning - Use of Industrially Produced Filler

Flow Properties of the Matrix Phase as a Function of the Filler's Specific Surface Area

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Mikroproporsjonering – Bruk av Industrielt Fremstilt Filler
- Matriksfasens Flyteegenskaper som en Funksjon av Fillerens Spesifikke Overflateareal

BY:

Helga Synnøve Kjos-Hanssen

SUMMARY:
Variation in water/cement-ratios (w/c), filler contents (fi/c) admixture dosages were measured. This resulted in twelve matrices with the Velde fillers to determine the matrix's flow properties for each of the cases. Including these, a redo of a set of matrices from a previous study to indicate the fundamental flow properties for the disturbed results, with the low admixture dosage.

For each of the matrices, the flow resistance, yield shear stress, plastic viscosity, and the mini-slump spread were measured and compared to one another. The flow resistance was found through flow progress in the FlowCyl-apparatus. The yield shear stress and the plastic viscosity were found through measurements done in the rheometer machine, while the mini-slump spread was found through the mini-slump spread measurement.

In order to investigate the relation between the flow properties with the specific surface area (SSA), each of the filler's SSA had to be calculated. This was done through retrieving the particle size distribution (PSD) from a combination of mechanical sieving and a SediGraph analysis. A PSD is the particle grading curve of a filler, indicating the mass percentage of each particle size. The SediGraph works best when the maximum particle size of the analyzed sample is 63 micron. The particles above 63 micron were taken care of by mechanical sieving. The SSA is calculated by summarizing the surface area per particle, within each particle size, and multiplying that with the mass percentage of each particle size.

Through the results, some of the admixture dosages, for both w/c's, were revealed to be insufficient to reduce the matrix's yield shear stress to a negligible level. The matrices with the sufficient dosages indicate the relationships expected between the different flow properties. This means that the conclusion is based on the filler's effect on the flow properties with both sufficient and insufficient admixture dosages.

What the results show is that when using a sufficient admixture dosage, the yield shear stress reduces to a negligible level. This implies that the matrix's flow resistance is closely related to the plastic viscosity. And the filler's effect on the flow resistance can be determined unambiguous and predictable with respect to SSA, given that a sufficient admixture dosage is used to reduce the yield shear stress to a negligible level.

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Summary

The effect of filler from crushed aggregates on the concrete rheology has been studied before in [1, 2, 3]. The results found in [1, 2] indicate that the filler's effect on the matrix's flow resistance, λ_q, and thus indirectly the plastic viscosity, μ, is unambiguous and predictable with respect to the filler's specific surface area (SSA). The results in [3] indicate that the filler's effect is not as unambiguous as first anticipated. The results were disturbed, probably due to the admixture dosage being too low to reduce the matrix's yield shear stress, τ_0, to a negligible level.

The purpose of this study is to determine if the disturbance in the results from [3] is due to the yield shear stress, through several rheological measurements. The major part of the measurements were performed with; two water/cement-ratios (w/c), three filler contents (fi/c) within each w/c, and two admixture dosages within each fi/c. This resulted in twelve matrices with the Velde fillers to determine the matrix's flow properties for each of the matrices. Including these, a redo of a set of three matrices from [3] to indicate the fundamental flow properties for the disturbed results. These matrices with the low admixture dosage.

The fillers used in this study were received from two aggregate producers, Velde AS (Velde) [4] and Feiring Bruk AS (Feiring Bruk) [5]. Both of Feiring Bruk's fillers and two of the fillers from Velde were pre-sieved prior to arriving to the Norwegian University of Science and Technology (NTNU). The intermediate filler (< 0.125 mm) from Velde was sieved from a sand mixture containing particles from 0-0.5 mm, at NTNU.

For each of the matrices, the flow resistance, yield shear stress, plastic viscosity, and the mini-slump spread were measured and compared to one another. The flow resistance was found through flow progress in the FlowCyl-apparatus. The yield shear stress and the plastic viscosity were found through measurements done in the rheometer machine, while the mini-slump spread was found through the mini-slump spread measurement.

In order to investigate the relation between the matrix's flow properties with respect to the filler's specific surface area (SSA), each of the filler's SSA had to be calculated. In order to calculate these SSAs, the particle size distribution (PSD) had to be retrieved from a combination of mechanical sieving and a SediGraph analysis. A particle size distribution (PSD) is the particle grading curve of a filler, indicating the mass percentage of

each particle size. The SediGraph, a sedimentation machine, has several parameters that need to be correct in order for the results to be reliable. Several runs with combinations of different parameters were performed to get the most reliable PSD, for 0-63 μm. The SediGraph works best when the maximum particle size of the analyzed sample is 63 μm. The particles $\geq$63 μm were taken care of by mechanical sieving. The SSA is calculated by summarizing the surface area per particle, within each particle size, and multiplying that with the mass percentage of each particle size.

Through the results, some of the admixture dosages, for both w/c's, were revealed to be insufficient to reduce the matrix's yield shear stress to a negligible level. The matrices with the sufficient dosages indicate the relationships expected between the different flow properties. This means that the conclusion is based on the filler's effect on the matrix's flow properties with both sufficient and insufficient admixture dosages. What the results show is that when using a sufficient admixture dosage, the yield shear stress reduces to a negligible level where no disturbance occurs. This implies that the matrix's flow resistance is closely related to the plastic viscosity. In addition, the filler's effect on the matrix's flow resistance is determined unambiguous and predictable with respect to SSA, given that a sufficient admixture dosage is used to reduce the yield shear stress to a negligible level.

Separate from the main purpose of this study, two fillers from Feiring Bruk were used in four matrices. The fillers ($<$ 0.125 mm) are extracted from larger sand fractions. The primary subbus from a 0-20 mm sand fraction, and the 0/2-filler from a 0-2 mm sand fraction. The matrices for both the fillers were within the same w/c-ratio, had the same admixture dosage, and were measured with two filler contents. The fillers were used as the intermediate filler in the same type of measurements done in the major part of this study. For these measurements, the intermediate filler from Velde worked as a reference filler.

The Feiring Bruk filler's effect on the matrix's flow resistance resulted in the primary subbus being ranked lower with regards to quality, than the 0/2-filler, due to its higher SSA, which resulted in a higher flow resistance. This means that the 0/2-filler's crushing method has a beneficial effect on the matrix's flow properties when it comes to the rheology.

Sammendrag

Effekten av filler på betongens reologiske egenskaper er tidligere studert i [1, 2, 3]. Resultatene i [1, 2] indikerer at fillerens effekt på matriksens flytmotstand, λ_q, og da også indirekte matriksens plastiske viskositet, μ, er entydig og forutsigbar i forhold til fillerens totale samlede overflateareal (SSA). Det ble stilt spørsmål ved denne entydigheten da tilsvarende forsøk ble utført i [3], og denne sammenhengen ikke var like entydig som først antatt. Resultatene ble forstyrret, trolig av for lav tilsetningsstoffmengde for å redusere matriksens flyteskjærspenning, τ_0, til et neglisjerbart nivå.

Målsettingen med denne masteroppgaven er å etterprøve tilsvarende forsøk som i [3], for å indikere om det faktisk var flyteskjærspenning som forstyrret resultatene fra [3]. Mesteparten av forsøkene omhandler; to masseforhold (w/c), tre fillerinnhold (fi/c) for hver w/c, og to tilsetningsstoffmengder for hver fi/c. Dette resulterte i tolv matrikser med bruk av Velde fillerne, for å fastslå matriksens flyteegenskaper for hvert forsøk. I tillegg til disse, ble tre matriksblandinger fra [3], med den lave tilsetningsstoffmengden som gav de forstyrrede resultatene, gjentatt for å fastslå de fundamentale flyteegenskapene.

Fillerne brukt i denne oppgaven ble levert av to tilslagsprodusenter, Velde AS (Velde) [4] og Feiring Bruk AS (Feiring Bruk) [5]. To av fillerne fra Velde og begge fra Feiring Bruk var ferdigsiktet da de ankom NTNU. Mellomfilleren (< 0.125 mm) fra Velde ble siktet ut av en sandblanding som inneholdt partikler fra 0-0.5 mm.

For hver av matriksene ble flytmotstand, flyteskjærspenning, plastisk viskositet, og mini-slump utbredelse målt og sammenlignet med hverandre. Flytmotstanden ble bestemt gjennom væskestrømsmåling i FlowCyl-apparatet, flyteskjærspenningen og den plastiske viskositeten gjennom forsøk i en rheometer maskin, mens mini-slump utbredelsen ble bestemt gjennom mini-slump utbredelsesmåling.

For å sammenligne flyteegenskapene med hver av fillerne's spesifikke overflateareal, må overflatearealet regnes ut. Dette blir gjort ved å hente ut fillerne's partikkelstørrelseskurve, PSD, gjennom en kombinasjon av mekanisk sikting og SediGraph-analyse. Fillerens partikkelstørrelseskurve viser masseprosentandelen for hver partikkelstørrelse i filleren. SediGraph'en, en sedimenteringsmaskin, har flere parametere som må stemme for at resultatene blir valid. Flere kombinasjoner av forskjellige parametere ble kjørt for å få den mest valide partikkelstørrelseskurven, for 0-63 μm.

SediGraph'en jobber best når den maksimale partikkelstørrelsen på den analyserte filleren er 63 μm. Mens det over 63 μm blir indikert gjennom den mekaniske siktingen. Overflatearealet blir regnet ut ved å summere overflatearealet til hver partikkel innenfor hver partikkelstørrelse, og multiplisere det med masseprosentandelen for hver partikkelstørrelse.

Resultatene viser at enkelte av tilsetningsstoffmengdene, for begge masseforholdene, ble utilstrekkelige for å redusere matriksens flyteskjærspenning til et neglisjerbart nivå. Mens matriksene med tilstrekkelig tilsetningsstoffmengde viste forholdene som var forventet mellom de forskjellige flyteegenskapene. Dette betyr at konklusjonen er basert på fillerens effekt på flyteegenskapene med både tilstrekkelige og utilstrekkelige tilsetningsstoffmengder. Resultatene viser at med en tilstrekkelig tilsetningsstoffmengde, blir flyteskjærspenningen reduserte til et neglisjerbart nivå hvor den ikke forstyrrer flytmotstanden. Dette bekrefter at matriksens flytmotstand er nært tilknyttet plastisk viskositet, og at fillerens effekt på flytmotstanden er entydig styrt av dens totale overflateareal for partiklene. Dette, med forbehold om at det brukes tilstrekkelig tilsetningstoffmengde for å redusere flyteskjærspenningen til et neglisjerbart nivå.

Separat fra hovedmålet med masteroppgaven, ble de to fillerne fra Feiring Bruk brukt i fire forsøk. Fillerne (< 0.125 mm) ble siktet fra sandblandinger som inneholdt større fraksjoner. Primær subbusen er siktet fra en 0-20 mm sandblanding, mens 0/2-filleren er siktet fra 0-2 mm sandblanding. Forsøkene med fillerne hadde likt masseforhold, lik tilsetningsstoffmengde, og utført for to fillerinnhold. Feiring Bruk fillerne ble brukt som mellomfilleren i tilsvarende forsøk som størstedelen av oppgaven. For disse forsøkene fungerte Velde sin mellomfiller som referansefiller.

Effekten av Feiring Bruk sine fillere på matriksens flytmotstand resulterte i at primær subbusen ble rangert lavere i forhold til kvalitet, enn 0/2-filleren, på grunn av dens høyere overflateareal, og derfor også høyere flytmotstand. Dette betyr at knusemetoden til 0/2-filleren har en fordelaktig effekt på matriksens flyteegnskaper når det er snakk om reologi.

Til farfar og morfar.
Dere har vist så mye entusiasme og beundring for meg gjennom hele studiet mitt. Det har gitt meg ekstra motivasjon til å fullføre, og for å gjøre dere ekstra stolte.

Farfar; Din vanvittige egenskap til å lese deg opp på, sette deg inn i, og bli oppriktig interessert i et hvert fagfelt barnebarna dine studerer, beundrer jeg deg for. Det er aldri et kjedelig øyeblikk rundt middagsbordet ditt. Tusen takk for at du er en del av heiagjengen min!

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Jeg er veldig glad i begge to. Denne oppgaven er til dere.
Hilsen Betong-Helga.

Preface

This master thesis is written as a mandatory ending to the integrated master, Civil Engineering, offered by NTNU, during the spring of 2016. The theme for this thesis is found under the major of Concrete Technology, by the Department of Structural Engineering.

The thesis is a continued work from the project thesis that I wrote during the fall of 2015 [3]. Materials received from two aggregate producers, Velde AS (Velde) [4] og Feiring Bruk AS (Feiring Bruk) [5], were examined to look at how the differences between the different crushing methods affect the matrix's flow properties. In addition, these aggregate producers were paid a visit to indicate how they run their business. There is also a little introduction to the research plan of the project BIA-KPN, the Mikroproporsjonering i Knust Sand (Micro proportioning with crushed sand) (MiKS)-project.

The thesis is written in cooperation with Skanska Norway AS (Skanska) and as a contribution to the MiKS-project. The professor and supervisor for the thesis was Sverre Smeplass, head of the Concrete Technology department in Skanska and Professor II at NTNU. The description of the thesis is formulated by Sverre Smeplass and myself.

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Helga Synnøve Kjos-Hanssen

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And last, but not least, to my parents Mette and Jens Jacob, and my siblings, thank you for cheering for me all the way to the finish line. I made it!

Contents

List of Figures

List of Tables

List of Symbols

λ_q	flow resistance.
μ	plastic viscosity.
τ_0	yield shear stress.
fi/c	filler/cement-ratio, filler content.
w/c	water/cement-ratio.
w/p	water/powder-ratio.

Acronyms, Initialisms and Terms

additive	supplementary cementitious materials such as: silica fume, fly ash and blast-furnace slag.
COIN	Concrete Innovation Centre.
mass balance	balance between produced and sold fractions at an aggregate producer.
MiKS	Mikroproporsjonering i Knust Sand (Micro proportioning with crushed sand).
NTNU	Norwegian University of Science and Technology.
OCC	ordinary compacting concrete.
PM-model	particle-matrix model.
powder	(cement+filler).
PSD	particle size distribution.
SCC	self-compacting concrete.
SSA	specific surface area.
VSI	vertical shaft impactor.
WG	work groups.

Chapter 1
Introduction

1.1 Background Information

The use of crushed aggregate materials in sand fractions for concrete production is expected to increase in the future. The reason for this is that natural gravel resources are limited. Current technology within the concrete production has enhanced due to new equipment that produces crushed sand with higher quality.

One of the challenges with the use of crushed aggregate is that all sand fractions contain a large amount of filler; particles $\leq 0.125\ mm$ $(= 125\ \mu m)$. If the filler cannot be used in the matrix or concrete, it will be deposited as waste. This is a bad alternative as seen from the resource and environmentally-friendly perspective.

Previous studies, an example in [8], have found that the use of large amounts of filler in the concrete production results in a decrease in workability, an increase in the yield shear stress, τ_0, and the plastic viscosity, μ. Thus larger amounts of cement are needed in the concrete. This is unfavorable with respect to both the economic and environmental point of view, due of the high cost of cement, and the high CO_2-emission related to the cement production. Because of this, it is important to study the effect of filler on the rheological properties of concrete and matrix.

The effect of filler from crushed aggregates on the concrete rheology has been studied as a subproject [1] to Concrete Innovation Centre (COIN) FA 2.1-programme (2007-2014) [9], in a PhD-thesis (2016) [2], and in a project thesis (2015) [3]. The results found in [1, 2] indicate that the filler's effect on the rheology of the concrete is highly unambiguous and predictable with respect to the filler's SSA when modern production equipment is in use. While the results in [3], tested on the matrix, indicate that the filler's effect is not as unambiguous as first anticipated. A check of the newly found results from [3] will be carried out in this study.

The use of filler is expected to provide a huge potential for management and adaptation of the concrete rheology for different common properties and uses. The rheological measurements are based on the PM-model, which presupposes a clear connection between the matrix and the concrete rheology when the particle phase and the volume ratio of matrix and particles remains unchanged.

1.2 Scope

The purpose of this study is to determine if the disturbances in the results in [3], are due to the yield shear stress, τ_0. If this comes true, then the filler's effect on the matrix's flow resistance, λ_q, and thus indirectly the plastic viscosity, μ, is unambiguous and predictable with respect to specific surface area (SSA), given that a sufficient admixture dosage is used to reduce the yield shear stress to a negligible level. This is checked through measurements with variation in several parameters, using industrially-produced filler from Velde AS (Velde) in Sandnes [4].

Separately from the main purpose, the effect of industrially-produced filler from Feiring Bruk AS (Feiring Bruk) in Lørenskog [5] using different crushing methods on the matrix's flow properties, will be measured. This is to indicate if the one crushing method has a beneficial effect compared to the other.

1.3 Thesis Description

The main purpose for this study is to observe the impact of industrially-produced filler on the matrix's rheological properties. Particularly, if the filler's estimated total specific surface area (SSA) can be used as a control parameter in proportioning of concrete, and matrix, and adaptation of concrete workability, with the help of a sufficient admixture dosage in concrete and matrix mixes, to be able to reduce the yield shear stress, τ_0, to a negligible level.

Velde is the Norwegian concrete and aggregates producer that has made the most progress in the production and the use of industrially-produces filler. In addition, it is interesting to see how Velde uses the fillers to control the properties of the different types of ready-mix concrete. It is especially interesting how the requirement of balance between produced and sold fractions at an aggregate producer (mass balance) in production affects the use of filler and thus the concrete's rheological properties.

Another aspect of this study is to get an introduction to the research plan for BIA KPN project Mikroproporsjonering i Knust Sand (Micro proportioning with crushed sand) (MiKS) and determine to what part of the research plan this study contributes.

Furthermore, fillers from two aggregate producers are used in the rheological measurements. The major part of the measurements, utilize fillers from Velde. The minor part of the measurements, utilize fillers from Feiring Bruk. The fillers from both the aggregate producers have differences in their crushing method. The fillers from Velde, undergo many crushing stages, including a final stage with the vertical shaft impactor (VSI), that give the filler particles a more spherical shape, which gives less SSA per mass unit, thus less need for cement. The fillers from Feiring Bruk, have undergone only one or two crushing stages, which give the particles a more angular shape, a higher SSA per mass unit, thus more need for cement. Differences will be determined through rheological and SediGraph measurements; the latter, to determine the particle size distribution (PSD) and SSA.

1.4 The MiKS-Project

The information gathered about the MiKS-project is collected from [10]. MiKS is a new 5-year project (2015-2020), Competence Project for the Business Community (KPN - Kompetanse Prosjekt for Næringslivet) led by NTNU and funded by the Norwegian Research Council, Norcem, Skanska Norway AS and Feiring Bruk AS. Direct questions about the project to Stefan Jacobsen, Professor at the Department of Concrete Technology, at the Institute of Structural Engineering at NTNU.

The purpose of the project is to develop the use of crushed sand in concrete production. Currently, concrete production consumes large amounts of sand and aggregates while natural sand resources are decreasing. It is important to find the best crushing method to get the best quality for the crushed masses in order to be able to replace the natural resources with the crushed masses.

This study is a contribution to the MiKS-project, but the work is done separate, the ambitions and goals are similar.

1.4.1 The Idea Behind MiKS

The idea is to enhance micro-proportioning of the concrete in order to be able to proportion, develop and exploit the properties of the filler together with binders (cement, supplementary cementitious materials such as: silica fume, fly ash and blast-furnace slag (additive)) and admixtures.

Table 1.1: Key points for the MiKS-project.

Technology	Filler has a large effect on the fresh concrete properties.
Resources and Environment	The goal is to preserve natural sand resources, reduce transportation of large amounts of sand, and make use of the fine particles that are by-products from the crushing process.
Technology, Environment and Economy	With the proper use of filler, the concrete composition (powder-/particle optimization) can become optimized with reduced binder and admixture consumption.

1.4.2 Contribution of This Study to the MiKS-Project

The project created proposals for seven work groups (WG) to get the entire scope of the project.

1. WG0 Administration
2. WG1 Full Scale Aggregate Production
3. WG2 Mapping of Material Parameters for Aggregates and Matrices
4. WG3 Material Models
5. WG4 Upscaling to Concrete Rheology
6. WG5 Full Scale Testing
7. WG6 Result Dissemination and Publishing

This study contributes to work within the WG3 - Material models. The main activity for WG3 is to simulate laboratory results with the help of computational fluid dynamic models, and to compare modelling, new and previously reported results. The purpose of this WG is to understand and utilize the underlying physics, as well as experimenting to establish empirical relationships between basic aggregate properties and functional flow properties for typical matrices. The deliverables will establish a micro-proportioning tool with a basic calculation model.

Chapter 2
Visit to Aggregate Producers

The rheological measurements performed in this study were with materials from two aggregate producers. The three filler fractions used in the major part of the measurements came from Velde AS (Velde) in Sandnes [4], and are the same fillers used in [1, 2, 3]. The minor part of the measurements were fillers from Feiring Bruk AS (Feiring Bruk) in Lørenskog [5].

All the information gathered in the following chapter is from the visits at the two producers, and through email correspondence with the producers.

Figure 2.1: A part of Velde's quarry in Sandnes.

2.1 Velde AS

2.1.1 About

Velde operates within quarries, rock drilling, transportation, ready-mix concrete, floor sanding, landfill, asphalt production and paving. In the quarry at Sviland in Sandnes, they have one of the world's most modern and environmentally friendly production plants for aggregates, asphalt, concrete and recycling. Velde has a turnover of 400 million NOK and has 150 employees [4]. They label themselves as 100% Eco-friendly.

The rock quarry in Sandnes was originally in the magnitude of 12 million tons, and Velde has 10 years to remove it. The quarry is of a good and homogeneous granite, optimal for Velde's concrete production. What makes Velde so unique compared to other crushed aggregate plants, is the fact that they use 100% crushed aggregates in their asphalt and concrete production. No other crushed aggregate plant does that. They have completely replaced the natural resource sand with high quality crushed sand.

Figure 2.2: The washing and sieving plant in Sandnes.

2.1.2 Production

The fact that Velde operates within multiple areas gives them an advantage compared to competitors in the market. They have great possibilities to try out new directions in some of their areas without it affecting the total production. This works well when some of the parts are independent from the others. This makes Velde less vulnerable to negative changes in the market.

Two main operations at the plant in Sandnes are the recycling of the incoming masses and the crushed aggregate production. The recycling production takes places in the washing plant, described in a later section. Of the incoming mass, Velde recycles up to about 70%. Because of the unknown origin of the incoming masses, they are not able to use these sorted masses in the main asphalt and concrete production. Some of it is used in concrete production with lower restraints. This makes the recycling production a separate one from the crushed aggregate production. As for the latter production, as mentioned in Section 2.1.1, all the aggregate fractions used in the concrete production, they crush themselves. The coarse aggregate goes through a mechanical sieving process, while the fillers go through a wind sieve. For more details about the crushing process see the next section.

Velde produces the same type of fractions that other aggregate plants do, but as mentioned earlier, it is all from 100% crushed supply. In addition to the aggregate fractions, they have a fraction type of finest particles, namely the filler (< 0.125 mm). The biggest challenge Velde has is to account for the entire mass balance. In their crushed aggregate production, in order to optimize their sand through the crushing stages, VSI and wind sieve, a large amount of fillers accumulates. The VSI especially produces more fillers than the normal aggregate production. With this surplus of fillers, the handling of mass balance gets tricky. Because of this surplus, unlike other plants and concrete producers, Velde has started using the fillers actively in all their asphalt and concrete production. This is to utilize the product, create new products and avoid depositing the product. However, it is not optimal yet; they are still trying to find more uses for the fillers.

A few years ago, Velde started mixing small amounts of filler into their concrete mixes to see how this would affect the rheology of the concrete, and to see if it was possible to actively adjust the properties of the concrete by addition of filler. This resulted in products with an increased amount of filler, and the property that followed, made the concrete more viscous and workable. This is not a desirable property for them or their customers.

Velde's areas are not always in production simultaneously; some of the areas are season-dependent. Like asphalt production, during the winter season there is a decrease in the production due to the colder weather, which makes paving more

difficult. As a result, this makes it that much more important to plan and predict what materials they might have a surplus of in the near future.

Crushing and Sieving Process for the Crushed Masses

At Velde in Sandnes, they have a large crushing and sieving process. They take in large amounts of quarry mass which go through five crushing stages that includes a final stage through the vertical shaft impactor (VSI). See details in Table 2.1.

The VSI grinds down the sharp edges of the crushed particles through impact crushing, and makes them more spherical. This is to achieve a lower specific surface area (SSA) of the particles, compared to a similar sized angular particle. A lower SSA lowers the need for cement, thus lowering the CO_2-emission related to the cement production, and makes the particles more suitable for the concrete production. The machine spins the particles around, and the grinding happens when the particles repeatedly hit the walls of the machine and each other.

After the crushing stages, the different mass sizes are sieved into one of the eight fractions they produce that the asphalt and concrete production use, and then stored in silos. In addition to those eight fractions, Velde also has smaller storage for fractions coarser than what the asphalt and concrete production normally use; for example, landfill for the roads.

Velde has three sieving stages; the first two explained are for the crushed aggregate production, while the third is for the recycled production. The first of the two is the mechanical sieving for the coarsest aggregates, and the second is a wind sieve for the smallest particles. The one for the smallest recycled particles is the wet sieving. The wind siever takes care of the 0/2 mm fractions. Velde is the only producer with a wind sieve, as of today.

Washing and Sieving Process for the Recycled Masses

The washing plant at Velde in Sandnes is one of the biggest in Europe [11]. This production takes care of the incoming masses and recycles them to different fractions. As shown in Figure 2.4, the mass comes in from the left and is roughly sorted before it continues through the entire plant. Everything $\geq$100 mm is characterized as over-sized, while the rest goes through the system.

The mass goes through three washing processes before it proceeds to the sieving section. The sieving section divides the masses into the desirable fractions, and the smallest of the particles go to the sedimentation pool. In this pool, a flocculant medium helps the particles settle to the bottom more rapidly.

Table 2.1: The crushing process at Velde AS.

#	**Crushing stages**	**Type of crushing machine**	**Function**	**Output sizes [mm]**
K1	Coarse	C160 std Nordberg Jaw Crusher	- Crushes the first input of masses	0/300
K2	Extra Coarse	GP500S Metso Cone Crusher	- Crushes the surplus sizes from K1 - Sieves into fractions - Recrushes the surplus sizes	20/80 - 0/18 - 0/22 - 0/4 - 4/16
K3	Coarse	GP300 Metso Cone Crusher	- Crushes 20/80 from K2 - Sieves into fractions - Recrushes the surplus sizes	Railway gravel (22/63) - 0/5 - 0/30 - 0/4 - 4/8 - 8/11 - 11/16 - 16/22
K4	Fine	HP3 Nordberg Cone Crusher	- Crushes the undefined fractions from K3 - Sieves into fractions	0/4 - 4/8 - 8/11 - 11/16 - 16/22
VSI	Fine	Barmac B9100SE DTR rotor	- Runs particles from K3 and K4 - Sieves into fractions	0/2 - 2/5 - 5/8 - 8/11 - 11/16 - 16/22
Wind sieving	Super Fine	AC30 GI, Wind sieve	- Runs particles from the VSI - Sieves into fractions	0/0.063 - 0.063/0.5 - 0.25/2

Figure 2.3: One of the washing stages in the recycling production.

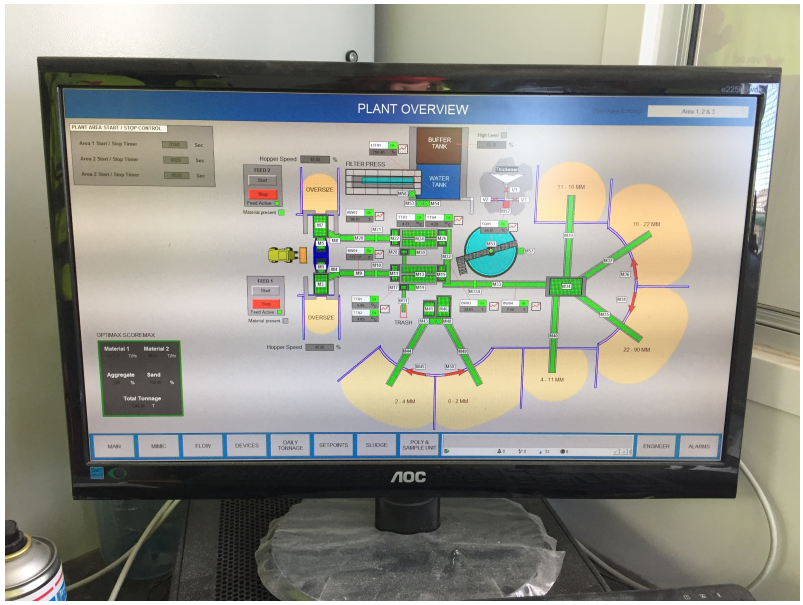


Figure 2.4: The plan overview of the recycling production, the washing and sieving plant in Sandnes.

Transport

In the concrete production, the transport of the concrete is important. In order to get the quality the customer desire at the right time, Velde has a computer system that calculates the driving time (takes in traffic information) and casting time. This makes the delivery optimal without unnecessary waiting.

2.1.3 Future Prospects

Velde has many new ideas the success of will definitely benefit their business. They are looking into possibly using the surplus of filler in ditch way concrete where the strength is not that important, and the main purpose is only to fill the ditch and perhaps dig it up later. Of the recycled masses, Velde wants to utilize it to a better extent than they currently do.

Velde would also like to expand their flooring business. They see an opportunity in the market and potential within the area. In addition to this, they see a positive side with more business, which will lower the expenses they have already invested in the machines. They want to publicize more to increase the production.

Velde would like to look into using the clay disposed by the washing process for something useful. Today they just deposit it.

When the asphalt of best quality comes in, they extract the bitumen (asphalt binder) and reuse this. They currently deposit the bad asphalt, but Velde plans to increase the degree of recycling of old asphalt.

2.2 Feiring Bruk AS

2.2.1 About

Feiring Bruk is a family owned business which primarily started as an aggregate producer. Over the years of development, the company grew to what it is today. They have 140 employees and their turnover for 2015 was 500 million NOK. [12]

With the past in memory and the future in focus, Feiring Bruk will be the industry's most significant supplier through highly skilled, service-oriented sales and sustainable resource management. [12]

Feiring Bruk is mainly an aggregate producer (10 quarries), but also has an asphalt production (two places), mobile rock crushers (18-19 crushers) and they receive different kinds of mass from others to either reuse or deposit. Feiring Bruk is able to reuse a large amount of delivered mass to landfilling. Examples of landfilling are a ground layer under a ski resort or residential area, to build terrain, and to stabilize landslide-prone areas.

Feiring Bruk's quarry is of gneiss and granite.

Figure 2.5: Feiring Bruk in Lørenskog.

2.2.2 Production

The majority of Feiring Bruk's production consists of paving and asphalt production. In addition, within the asphalt area Feiring Bruk recycles old and used asphalt and breaks it down to reuse the different components. They reuse almost 100% of the different parts and with the bitumen (asphalt binder), they recycle all of it. This is great relative to the saving of the CO_2-emission associated with the production of bitumen. As for the crushing production, they produce only the coarse aggregate needed in their asphalt and customer's concrete production. Feiring Bruk deposits the sand and the fillers.

A challenge Feiring Bruk has is to get the mass balance stable with the large amount of 0/4 mm surplus. They have not found a use for the fillers yet, but they are constantly trying to find an area to dispose of it. Some of it they use in the asphalt production, but that is not sufficient. They admit that they have a slightly disadvantage when it comes to not owning their own concrete production. A self-owned concrete production would let them experiment with the fillers, as Velde does.

Figure 2.6: A part of Feiring Bruk's quarry in Lørenskog.

Crushing and Sieving Process

Feiring Bruk's crushing process consists of four crushing stages: First and the coarsest crushing – coarse – intermediate – fine. Depending on the fractions, the material goes through the necessary crushing stages before the machines sieve them into different fraction silos. The stages and machines are described in Table 2.2.

As mentioned in the previous section, Feiring Bruk has a large surplus of the 0/4 mm fraction. They have not optimized this surplus. This makes it less suitable for use in concrete production, and today they deposit it. This surplus would be more suitable if Feiring Bruk had a VSI. The VSI makes the fillers suitable by grinding down the particle edges. Because they do not have the VSI, Feiring Bruk then delivers more angular particles, with larger SSA, to their customers. The particles that go through some or all of the crushing stages undergo a natural grinding of the edges, but can never become as spherical as with a VSI.

Table 2.2: The crushing process at Feiring Bruk

#	Crushing stages	Type of crushing machine	Function	Output sizes [mm]
1	Coarse	Svedala P180/140 Jaw crusher	- Crushes the first input of masses	0/22 22/120
2	Coarse	Morgårdhammar BS900 Superior crusher	- Recrushes the surplus sizes from #1	Crushes >120 to 0/250
3	Intermediate	Sandvik CH 660 Cone crusher Svedala 36" (recrusher)	- Crushes the output from #2 - Sieves into fractions - Recrushes the surplus sizes from the crushing	Crushes 0/250 to 0/100 Sieves 0/63 from 0/100 to 0/8 - 8/16 - 16/32 - 32/63 Recrushes 63/100 from 0/100
4	Fine	Svedala H-4000 Cone crusher	- Crushes two fractions from #3 - Sieves the output - Recrushes the surplus sizes from the sieving	Crushes 16/32 and 32/63 to 0/16 Sieves 0/16 to 0/4 - 4/8 - 8/11 - 11/16

2.2.3 Future Prospects

After seeing the advantages of having a washing plant at other aggregate producers, Feiring Bruk has ordered one for themselves. This is to wash their crushed masses, to deposit all particles $\leq$63 μm, and to be able to split the masses into smaller fractional parts, than for the types of fractions they currently have, for instance, 0/150 mm and 0/200 mm.

2.3 Differences

Velde and Feiring Bruk are two aggregate producers of the same magnitude when it comes to turnover and employees. When breaking down the two, the main difference is the quality of the products they deliver. They produce the same kind of fractions with similar crushing methods up to a point where Velde includes the VSI and wind sieve. With the VSI and wind sieve, Velde makes sure the particles surface results in a more spherical shape, thus less SSA and less need for cement. Rather than the angular particles from Feiring Bruk, which give higher SSA, thus higher need for cement. The VSI and the wind sieve makes Velde's fillers more suitable for concrete production,in that matter. Feiring Bruk deposits the fillers and are left with a mass balance that becomes harder to balance out. If Feiring Bruk took the technical step of acquiring a VSI and a wind sieve, they could obtain the same output as Velde.

Velde has an approach to solve the challenge with the mass balance by optimizing the fillers in order to use them actively in their asphalt and concrete production. Since Feiring Bruk does not have a VSI and a wind sieve, they cannot accomplish the same in their asphalt production.

Velde makes themselves unique in the market when it comes to environmentally-friendly production. As the only one in Norway, they use 100% crushed aggregate and fillers in their production, instead of using natural resources. They actively use the fillers as a primary product in their production. Coarse aggregate goes to Feiring Bruk's asphalt production and the customer's concrete production. They deposit the fillers.

Chapter 3
Theory

3.1 Particle-Matrix Model

The following information and details about the particle-matrix model (PM-model) is collected from [2], [6], [13], while the setup of this chapter is collected from [3].

PM-model is a model developed by Ernst Mørtsell in his dissertation at NTNU in 1996 [14]. The slump value defines the model, and the properties of the two phases the model is divided into, describe the workability of the concrete. These two phases are the matrix phase (a liquid material) and the particle phase (a frictional material). The plastic viscosity, μ (how long it takes to flow out), and yield shear stress, τ_0 (the yield point for the liquid to begin to flow), characterize the liquid material. While air voids and how well the particles pack together, characterize the frictional material.

The idea behind the PM-model is to simplify the way to observe and control the workability of the concrete. The concrete usually consists of several components (up to eight), but instead of looking at all eight components separately, the PM-model divides these components into two phases: the matrix and the particle phase [6].

The matrix phase. This phase contains a mixture of all materials with sizes $\leq 125\ \mu m$. This includes water, admixtures, binders like cement and additive, and aggregates like fines $\leq 125\ \mu m$. The matrix phase is a viscous fluid characterized as other fluids.

The particle phase. This phase contains what not is included in the matrix; aggregates $\geq 125\ \mu m$. The water content already existing within the pores of the aggregate is included in the particle phase, which increases the density. This phase consists only of dry materials, which gives it a good reason to be determined as a frictional material.

When mixing the matrix and the particles to the well-known material, concrete, the matrix fills the air voids between the particles. If particles have a size below a certain value, the behavior of the particles depends more on the surface area and surface properties than their shape and gravity, especially when the particles disperse in water.

3.1.1 Parameter Characterization

The particle-matrix model (PM-model) is based on a single parameter characterization for each of the two phases. For the matrix phase, it is the flow resistance, λ_q, and for the particle phase it is the air voids and how well the particles are packed together. Details of these parameters are taken from [6].

The Flow resistance, λ_q, describes how viscous (high λ_q = close to 1) or liquid (low λ_q = close to 0) a matrix or concrete is. The flow resistance is determined through FlowCyl-measurements. The FlowCyl-apparatus measures the flow progress of the matrix. The matrix flows through the apparatus and into a container located on an electronic scale connected to a computer. This computer logs all the measurements. More details about the FlowCyl-measurement, see Section 4.5.1.

The FlowCyl measures the liquid flow out of the apparatus and compares it with a liquid flow of an ideal fluid (λ_q=0). The FlowCyl-results come out as points in a graph, see Figure 3.1. A spreadsheet is made to calculate the flow resistance [15]. The spreadsheet creates a curve through these FlowCyl-points in the figure, a kind of summation curve for normalized measurement values. The curve values turn out slightly different from the actual measured values. This is because the curve generates from a polynomial, a formula, where the new curve adapts to the points through the least square mean algorithm. The mean values for these curves help calculate the flow resistance. Taking the values of the ideal liquid flow and subtracting the normalized values of the measured liquid flow (the matrix), calculates the flow loss. Finally, calculating the flow resistance by dividing the mean values of the flow loss of the normalized values for the ideal liquid flow. For more detailed explanation of the calculation of the flow resistance, see the appendix in [6].

Air voids/packing, explains the properties of the particle phase. It is possible to define it in two ways; either through the air void content, or the particle content of the particle phase (packing).

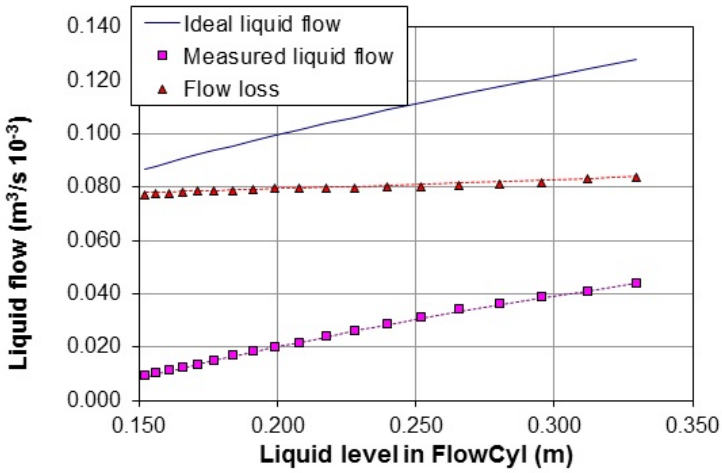


Figure 3.1: The liquid flow graph for the matrix mix number 14 - w/c=0.59, and admixture amount=0.25%/powder

The particles in this section are $\geq 125\ \mu m$. The air void content means the air that is in a container containing particles. Taking the entire volume (air + particles) and subtracting the volume of particles, what is left is the air void content, also called the porosity. Packing is the opposite; what is left when the air content is subtracted from the entire volume. Taking the container density with the particles inside, and dividing this by the particle density, calculates the packing. Knowing the particle size distribution (PSD) and how the particles are located relative to each other is necessary to find the container density.

The interesting thing seen in a particle-matrix point of view is how much air void the matrix will fill up. If the amount of matrix exceeds the air void content, this will affect the slump value. The more matrix, the higher the slump value.

3.1.2 Specific Surface Area (SSA)

To calculate the specific surface area (SSA), the knowledge about the mass percentage of each particle size, has to be obtained. This is done by performing a particle size distribution (PSD). In this study, the PSD is retrieved through mechanical sieving and a SediGraph analysis. More information about the SediGraph analysis in Section 4.3.

For crushed aggregate fines passing a 63 μm or a 125 μm sieve, generally about 50% of the surface area is concentrated among particles $\leq$5.0 μm of equivalent sphere size. This is because the ratio of surface area to volume increases in a manner that is inversely proportional to particle size[2]. For this study $\geq$ 50% of the surface area is concentrated $\leq 10\mu m$ particle size. The SSA dominates more when the particle size decreases. This implies that smaller particles influence the rheological properties to a larger extent.

A statement about SSA of cement: *A high specific surface area implies that the reactive surface of the cement towards water is high. This promotes the hydration and thus the heat and early-strength development*[16].

Calculation of the Specific Surface Area (SSA)

Calculation of the specific surface area (SSA) is necessary to figure out the applicable filler combinations to show the connection between flow resistance, λ_q, and SSA. The general surface area is calculated on the basis of the average particle diameter within each range of particle size, where spherical particles are assumed. See equation below, r=particle radius, d=particles diameter. The average particle diameter is found through mechanical sieving and a SediGraph analysis that obtains a particle size distribution (PSD).

$$\text{General surface area} = \frac{area}{volume} = \frac{4\pi r^2}{\frac{4}{3}\pi r^3} = \frac{3}{d/2}$$

While the SSA is found by calculating the surface, for instance of 1.0 kg or 1 mm^3, of a filler with a certain grading. The SediGraph can register particle sizes down to 0.1 μm, but due to uncertainties related to particles $\leq$ 1.0 μm, the lowest particle size chosen for this study in the calculation of the SSA is 1.0 μm.

$$SSA = \sum_{d=1.0\ \mu m}^{d=125\ \mu m} \frac{3}{d/2} \cdot (\text{Diff. diameter volume\%})$$

This approach is not completely accurate, but will provide a good basis for comparing particle grading of the same origin and manufacturing process. The calculated SSA's for this study are presented in Section 5.1.4.

3.1.3 Workability

Information about workability is collected from [2, 6, 7, 13], and the set-up is gathered from [3]. It is possible to see how the workability is characterized when the terms and concept of the PM-model are more understandable. The workability describes the properties of fresh concrete and depend on various parts, such as:

- Properties of the involved components
- The concentration - the amount of each component
    - For instance; How the filler content contributes to changes in flow resistance and matrix volume. [13]
- Physical and chemical interactions between components

The PM-model is a rough simplification defining the workability of concrete by only one parameter, the slump value. While in reality, several parameters can define workability. Fresh concrete could in that matter be characterized as a Bingham fluid. Normally the matrix is perceived as a Bingham fluid as well, as it is in this study.

Figure 3.2 shows the three defining parameters for variating the workability, thus for the PM-model. The first parameter indicates variation in the workability through the properties of the particle phase. For instance, by adjusting the amount of aggregate (the coarse particles), which varies the air void. The second parameter vary the workability by modifying the matrix's properties. While the third parameter varies through the volume ratio between the matrix and particles, specifically by increasing the matrix volume.

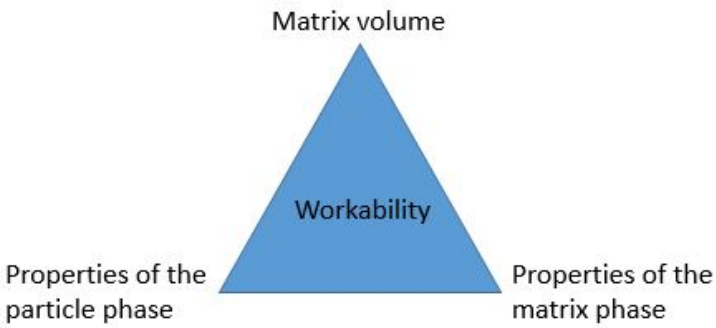


Figure 3.2: The three defining parameters for variating the workability, thus for the PM-model [6].

A Bingham fluid

A Bingham fluid defines workability with two matrix parameters, the yield shear stress, τ_0 and the plastic viscosity, μ. The relationship between these two parameters is displayed in Figure 3.3. The graph is actually for concrete, but is also representative of the matrix. Yield shear stress is normally low in the matrix material, and high in concrete. For a Bingham fluid, the following relationship holds [7]:

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

Where τ is the matrix's shear stress [Pa], τ_0 is the yield shear stress value [Pa], μ is the plastic viscosity [Pa*s], and $\dot{\gamma}$ is the rate of shear [1/s].

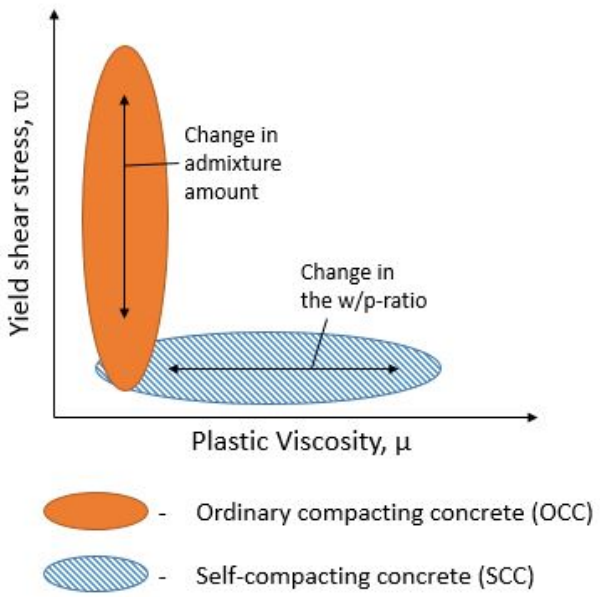


Figure 3.3: The rheological model, The Bingham fluid relationship, in terms of yield shear stress and plastic viscosity [7].

The matrix is measured by finding its flow resistance, λ_q, through the flow progress in the FlowCyl-measurements. In order to find the flow resistance, the yield shear stress has to be reduces to a negligible level. This implies the matrix to still be a Bingham fluid, but with a small and negligible contribution from the yield shear stress during the measurements. The matrix's flow resistance in that matter will lead to be primarily related to the matrix' plastic viscosity, and less affected by small variations in the matrix's yield shear stress.

The matrix's and concrete's plastic viscosity behavior is commonly determined through the mini-slump spread measurement. This relationship is then bound to be linearly distributed throughout the results. The common method that indirectly determines the concrete's yield shear stress is the slump value. And for a matrix, it is the mini-slump value (not the same as mini-slump spread used for plastic viscosity determination). For this study's matrix, the corresponding mini-slump values are not included due to the very flowable matrix. To replace the mini-slump value, the mini-slump spread together with results from the rheometer machine (Section 4.5.3) determine the matrix's yield shear stress in a less direct way. The result of how the mini-slump spread determines both the plastic viscosity and the yield shear stress will be interesting.

To be able to present the fresh properties in a graph, it is necessary to use the graph of *when the unloading or reducing the rate of shear takes place, the concrete (here: matrix) will have approximately viscous behavior all the way down until it is at complete rest* [7]. See Figure 3.4. This implies that the material has a elastic shear capacity. And it needs to be loaded up to τ_0 (the lowest shear stress) before it starts to flow [7].

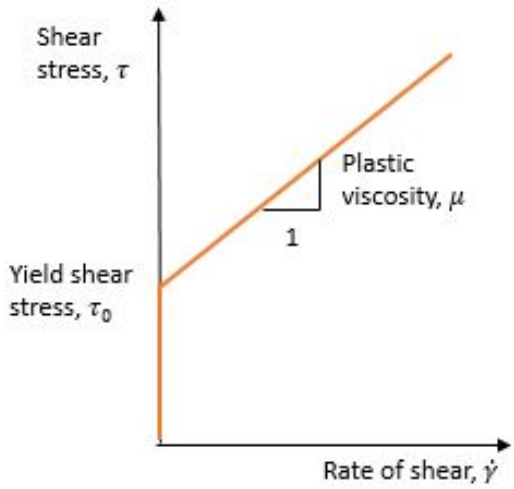


Figure 3.4: The Bingham Fluid Model relationship, collected from [7].

Functionality of a Bingham Fluid

Figure 3.3 displays how a Bingham fluid works. The ordinary compacting concrete (OCC) shows little variation around a relatively low plastic viscosity, μ, but a large variation in yield shear stress, τ_0. The variation in yield shear stress is due to the used admixture dosage. Opposite for the self-compacting concrete (SCC), there is little variation around a low yield shear stress, but rather large variations in plastic viscosity. The change in plastic viscosity is due to the different water/powder-ratio (w/p).

The difference between self-compacting concrete (SCC) and ordinary compacting concrete (OCC) is that when using a sufficient dosage of admixture, the yield shear stress becomes negligibly low that it has little influence on the flow resistance, λ_q, in the FlowCyl. This means that measured flow resistance will be an almost unambiguously expression of the plastic viscosity. The wide variation in plastic viscosity of SCC makes it unstable, unlike OCC which becomes more stable. It is assumed that the behavior of the matrix will be in the area where SCC is located.

In [3], the dosage of admixture was low and constant, and the only variation was in the w/p-ratios. However due to the chosen low admixture dosage, the flow resistance may have been disturbed by the yield shear stress. Because of this, the admixture dosages for this study are both increased and decreased from [3], to see how this influences the yield shear stress. While the same variations in the filler content (fi/c) and w/p are used, w/p is directly related to the fi/c within the same water/cement-ratio (w/c).

3.2 Particle Size Distribution

A particle size distribution (PSD) is a grading curve *determining the mass fraction of particles passing a sieve with square openings of minimum edge length 63 μm* [2], and through a SediGraph-analysis. The SediGraph works best when the maximum particle size of the analyzed sample is 63 μm. The particles $\geq$ 63 μm were taken care of by mechanical sieving. This is done to get the most accurate PSD for the specific filler.

What is applicable here is determining the mass percentage of the finer content in the fillers used in the rheological measurements. The curve that comes out of the SediGraph-measurements is commonly S-shaped. Where it curves depends on where the major part of the different sizes are.

3.3 Particle Shape

Does the particle shape influence the effect that the filler has on rheological properties, or is it dominated by the specific surface area (SSA)?

The amount of water and particles in the matrix affect the particle concentration more than the particle shape of the particle. In Table 3.1 the particle concentration of the water/cement-ratio (w/c) 0.39, 0.59, and 0.79 are displayed. w/c describes the particle concentration of the matrix, thus how viscous the matrix is. The higher water content in the matrix, indicates more space between the particles, which result in less interaction between the particles. The less interaction, the less effect the particle shape has on the flow properties. An angular particle shape, for instance, indicate a higher SSA, and a more viscous matrix. If the particle concentration is around 50%, as shown in Table 3.1, and interaction between particles are kept to a minimum, and the particle shape will not have any big influence in the final results.

Compared to a concrete recipe, the particle concentration is usually around 70-80% of the total volume. A high particle concentration results in a higher occurrence of particle interaction, which indicates that the particle shape affect more in a concrete than a matrix. What ends up affecting the forces between the particles and the water, are the surface area and surface properties, and not the particle shape and weight [6].

Table 3.1: Particle concentration in the different w/c-ratio matrices.

w/c	**0.39**		**0.59**		**0.79**	
fi/c	0.32		0.51		0.70	
	w	**par**	**w**	**par**	**w**	**par**
Particle concentration [%]	46.8	53.2	53.7	46.3	57.8	42.2
w = water | c = cement | fi = filler | par = particles						

3.4 Micro Proportioning

Micro proportioning is how to mix the matrix in the best way, in order to optimize volume and flow properties; to use different parameters to control the matrix properties in fresh concrete. For this study, two water/cement-ratios (w/c=0.59 and 0.79) were chosen, and the admixture dosage worked as the variation parameter. Normally the filler contribution from the aggregate, in a concrete, is small and given, but here it is managed actively with the cement. This means that micro proportioning is about using the fillers as a primary parameter for controlling the matrix flow properties. More details about micro proportioning in [2].

3.5 Hypothesis

This study is based on the results from [3], shown in Figure 3.5. The figure shows disturbances in the results (peaks in the middle values), that probably are due to a non-negligible yield shear stress, τ_0. The main purpose is to verify if the disturbance is related to the yield shear stress. Does the yield shear stress reduce when increasing the admixture dosage? If so, the matrix's flow resistance, λ_q, is described unambiguously by the specific surface area (SSA), given that a sufficient admixture dosage is used to reduce the yield shear stress to a negligible level. The SSAs in the Figure 3.5 and Figure 3.6 cannot be directly compared due to the different methods used to determine the particle size distribution (PSD), and thus the SSA.

To find the filler's effect on the matrix's flow resistance, measurements through a FlowCyl are performed. A FlowCyl is a vertical cylindrical steel pipe, with a narrow nozzle outlet cone at the end. The matrix is filled in the steel pipe, and poured out of the narrow outlet, into a container located on an electronic scale connected to a computer registering the flow progress. This is previously mentioned in Section 3.1.1. For more details about the execution of the measurements, see Section 4.5.1.

The matrix is perceived as a Bingham fluid, in the same way as a concrete. A Bingham fluid is characterized by the yield shear stress and the plastic viscosity, μ, as previously mentioned in Section 3.2. To determine these parameters (τ_0 and μ), supplementary rheological measurements in a rheometer machine and the mini-slump spread, are performed. In order to run the flow resistance measurements without interference, this mentioned yield shear stress has to be low enough to be neglected. The matrix results in a viscous fluid, which means that the it's behavior will lead to primarily be related to the plastic viscosity, and less affected by small variations in the yield shear stress.

As mentioned Section 3.2 about 'A Bingham fluid', the matrix's plastic viscosity behavior is commonly determined through the mini-slump spread measurement, while for the matrix it is the mini-slump value. Because the mini-slump value is not included in this study, the mini-slump spread together with results from the rheometer machine (Section 4.5.3), will determine the yield shear stress. How the mini-slump spread can determine both the plastic viscosity and the yield shear stress remains to be discussed in the results.

It will be interesting to see how the behavior between the yield shear stress and the plastic viscosity holds according to Figure 3.3. The yield shear stress, occurs in the interaction between the matrix liquid on the walls inside of the FlowCyl-steel pipe. Variations in the admixture dosage alters the value of yield shear stress. The higher dosage, the lower the yield shear stress.

The flow resistance is found through the flow progress in the FlowCyl. The flow resistance is affected by several material parameters. The water/cement-ratio (w/c) describes the particle concentration (Table 3.1) of the matrix, thus how viscous the matrix is. The higher water content in the matrix, the more space between the particles, which result in less interaction between the particles. The less interaction, the less effect the particle shape has on the flow properties. An angular particle shape implies a higher SSA, and a more viscous matrix. If the matrix has a particle concentration of about 50%, and the interaction between particles are kept to a minimum, then the particle shape will not have any big influence on the final results.

The filler itself can affect the flow properties in several ways. The origin of the filler, thus the rock type, affects the reactions in the matrix. Between the filler content (fi/c) and the fineness of filler, there is an uncertainty about which of the two influence the flow properties more. The filler content affect the flow properties by the total amount of filler per cement content in the matrix. The higher the filler content, the more viscous the matrix, while the major effect of the fineness of the filler, is that the finer the particle, the more particles per mass unit there is room for. This relates to a higher SSA, more need for cement to cover the surface area, thus a more expensive matrix (and concrete), due to the high cost of cement.

The effect of the filler content and the filler fineness characterized by the fillers SSA, is probably limited to matrices with a particle concentration within a certain range (perhaps 30-70%). When the particle concentration becomes too large (say around 70%), the particle phase parameters (air voids/packing, particle shape, frictional properties), needs to be taken into consideration. The particle phase parameters are neglected for this study, due to the particle concentrations of the measured matrices are about 50% (Table 3.1). In this study only variations in the filler content are taken into consideration; alternation in the fineness will not be discussed.

The SSA is calculated by performing a particle size distribution (PSD) through mechanical sieving and a SediGraph analysis (see Section 4.3). The cumulative mass percentage of the particle diameters are detected through the analysis. The SSA is calculated by summarizing the product of the area/volume-ratio for each of the average particle sizes within each mass percentage, multiplied with the cumulative mass percentage of each of the particle diameters (Section 3.1.2). It is presumed that the fine filler from Velde AS (Velde) has the highest SSA, followed by the intermediate one, and then the coarse.

The disturbances from the yield shear stress, in the [3]-results, are displayed in Figure 3.5. The w/c=0.79-results, were assumed to be more linearly related, like the w/c=0.39 and 0.59-results, then they turned out. The peak in the w/c=0.79-results is probably related to the disturbance of the yield shear stress. Since the main focus of the FlowCyl-measuring is performing the measurements with a negligible yield shear stress, then new measurements (for w/c=0.59 and 0.79) were performed in this study.

Separately, the effect of fillers produced with different crushing methods will be measured with respect to SSA. The fillers in question are the two fillers from Feiring Bruk AS (Feiring Bruk), and the intermediate filler from Velde, the latter, used as the reference filler. Velde's crushing method consists of several crushing stages, which end with a vertical shaft impactor (VSI), resulting in a spherical particle shape, thus a lower SSA. The two fillers from Feiring Bruk are taken out after the first (primary subbus) and the second (0/2-filler) crushing stage, and result in a more angular particle shape, with presumably higher SSA (Chapter 2). How will the two fillers from Feiring Bruk be ranked compared to one another? Does one of the crushing methods on the industrially-produced filler have a beneficial effect on the matrix's flow properties when it comes to the rheology?

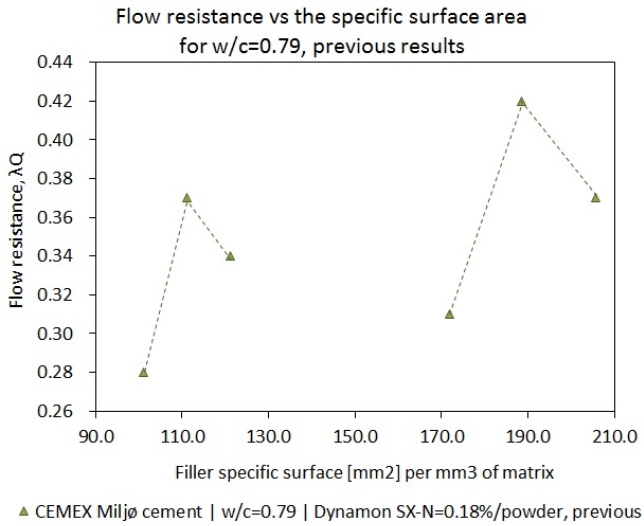


Figure 3.5: The flow resistance vs. the specific surface area. Results from [3] (water/cement=w/c=0.79). The left side results are related to the reference filler combination (also used here), while the right side results are related to the fine filler combination (will not be measured here).

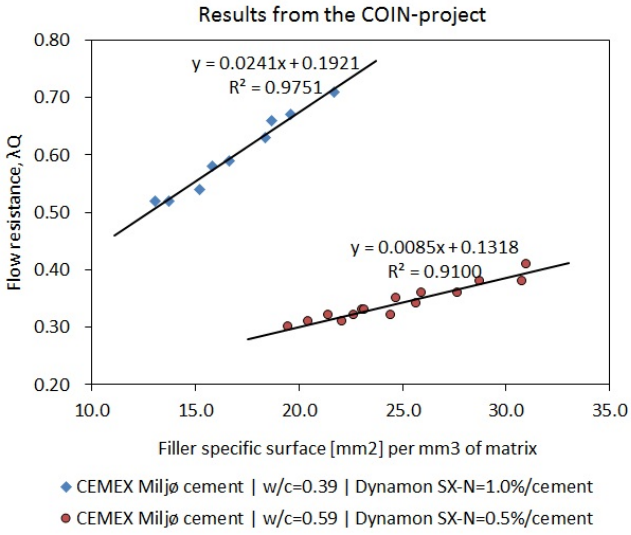


Figure 3.6: The flow resistance and the specific surface area relationship. Results from [1], water/cement=w/c=0.39 and 0.59

Chapter 4
Tests in the Laboratories

The mixing, the and mini-slump spread measurements were performed in the NTNU concrete laboratory, while the rheometer measurements were performed in SINTEF's concrete laboratory.

4.1 Materials

4.1.1 Filler

Filler from two aggregate producers were used in the measuring of the different rheological properties. For the major part of the measurements, where the admixture dosage varies, three basic fillers from Velde AS (Velde) were used. These are the same fillers used in [1, 2, 3]. By using the same filler, results in this study can be compared to the previous results.

For a minor part of the measurements, where the crushing method varies, two fillers from Feiring Bruk AS (Feiring Bruk) are used. These have gone through a different crushing method than Velde's fillers, and measurements will be performed to see if there is a difference between the fillers from different aggregate producers.

The three basic fillers received from Velde are shown in Table 4.1. The sizes of the three fillers are divided into fine, intermediate and coarse. The coarse is defined by the range [0.063 / 0.125 mm], but it does contain particles $\leq$0.063 mm as well. The fillers from Feiring Bruk are extracted from larger fractions. The primary subbus from a 0-20 mm sand fraction, and the 0/2-filler from a 0-2 mm sand fraction, as displayed in Table 4.2. Both the fillers were pre-sieved at their plant in Lørenskog before arrival at NTNU. The origin of the fillers from both of the aggregate producers is granite and gneiss

Table 4.1: The filler fractions of the basic filler, as used at Velde. Table collected from [1].

Fine filler	0 / 0.0625 mm	The finest filler fraction obtained from the wind sieve, mostly used in asphalt production. The fraction is used unmodified for these measurements. This filler was pre-sieved at Velde.
Intermediate filler	0 / 0.125 mm	Mostly used in concrete production. Particles $\geq$ 0.125 mm were taken out, during sieving. This filler was sieved at NTNU.
Coarse filler	0.063 / 0.125 mm	Mostly used in concrete production. Particles $\geq$ 0.125 mm were taken out, during sieving. This filler was pre-sieved at Velde.

Table 4.2: The filler fractions from Feiring Bruk.

Type	**Fraction size from the crushing process**	**Pre-sieved size**	**Amount**
From the first crushing stage (Primary subbus)	0-20 mm	0/0.125 mm	6.8 kgs
From the second crushing stage (0/2-filler)	0-2 mm	0/0.125 mm	8.0 kgs

Filler Composition

All the measurements were performed with the reference combination shown in Table 4.3, collected from [1]. The table shows the percentage of each basic filler in the combination. For the measurements with the fillers from Feiring Bruk, the intermediate filler, from Velde, is switched with the desired filler from Feiring Bruk.

Table 4.3: Filler combination used in this study. Table collected from [1].

Filler combination	**Fine**	**Intermediate**		**Coarse**
		Feiring Bruk	**Velde**	
Reference	10 %	50 %		40 %

Sieving of Velde's Intermediate Filler

The explanation of the sieving process of Velde's intermediate filler is collected from [3]. The intermediate filler was sieved at the concrete laboratory at NTNU. Velde sent a bucket of about 30 kgs of a sand mixture containing about 60% of particles ≥ 125 μm (particle phase). In the matrix measurements, only particles ≤ 125 μm were used, and everything above was sieved away.

The sand mixture received from Velde was moist upon arrival. A moist sand mixture is very difficult to sieve because the sand particles clogs together. In order to be able to sieve the filler, the mixture was dried for 24 hours in a heating cabinet at 105 °C. This made the intermediate filler completely dry.

The sieving process contained a set of sieves; 0.5 mm, 0.25 mm and 0.125 mm. Three sieves were used in order to reduce the risk of clogging, and to make the sieving process faster.

From the information given by Velde, the sand mixture should contain about 40% of intermediate filler. After the sieving, the filler was weighted to be 38% of the content, which is a reasonable percentage. The total amount of intermediate filler resulted in 11.5 kgs.

Water Absorption

As mentioned in the previous section, the intermediate filler was completely dried upon arrival. The two other fillers from Velde, and the two fillers from Feiring Bruk, were not dried like the intermediate one. In order to take account for the water absorption in all the fillers, the water absorption for all the fillers were assumed to be at 1.0%. The amount of water needed to reach 1.0% moisture content in the particle was added to the matrix recipe.

A sample of the two remaining fillers from Velde and the two from Feiring Bruk were heated overnight in the same heating cabinet as for Velde's intermediate one. This was to establish their moisture content. The percentages are displayed in Table 4.4.

By adding extra water to the matrix mixes, the final total matrix volume will increase slightly. However, it will not make a significant impact.

Table 4.4: Water absorption in the fillers.

Filler	**Moisture content**	**Addition of water in the matrix**
From Velde		
Fine	0.53 %	+ 0.47 %
Coarse	0.13 %	+ 0.87 %
Intermediate	0.0 %	+ 1.0 %
From Feiring Bruk		
Primary subbus	0.78 %	+ 0.22 %
0/2-filler	0.48 %	+ 0.52 %

4.1.2 Cement

The cement type used is CEMEX Environmental Cement. This cement contains supplementary cementitious material, namely about 33% of blast-furnace slag. See Table 4.5. The same cement was used in [1, 3]. CEMEX is a regular cement for all-purpose use. Velde themselves use this cement. The certified data sheet of this cement is in appendix A.

Blast-furnace slag contains both calcium and silica in glassy phases. It is described as latent (delayed) hydraulic (reacts with water) because the lime-silica-water reaction is very slow without the addition of an activator (either calcium hydroxide or sulphate).[17] *Note that slag is predominantly used in blended cements, and very rarely used as an addition added at the concrete production site.*[17]

This means that for the measurements in this study, the slag is an additive pre-mixed with the regular cement. The slag affects more the hardening part of concrete, which means other than the slag's particle size (1-100 μm, same as regular cement), it will not affect the results in any mentionable way. Moreover, the fact that all the measurements use the same cement means that there will not be any difference caused by the cement.

Table 4.5: Cement information, table collected from [1]

Type	**Amount and type of admixture**	**Fineness, Blaine (m^2/kg)**
CEM II/B-S 52,5 N	Slag, 30 %	460

4.1.3 Admixture

Information and details about the admixture type are collected from [1]. The admixture used is Mapei Dynamon SX-N. This is a widely-used super plasticizer based on modified acrylic polymers. The solids content of this admixture is 18%. The certified data sheet of this admixture is in appendix B.

For this study, the admixture dosage is determined as a percentage of the total amount of powder. For comparison, in [1, 3], the admixture dosage was determined as a percentage of total amount of cement. See example in Table 4.6.

For the previous measurements with w/c=0.79 [3], the original dosage of admixture was too low. For this study, new measurements with increased dosage were performed. As for the recent measurements with w/c=0.59 from [1], new measurements were performed with both increased and decreased admixture dosages.

4.2 Project Parameters

In order to determine the outcome of the rheological properties, project parameters have to be selected to do this. For all the measurements the reference filler combination was chosen to be the overall combination. Variations in water/powder-ratio (w/p) and in filler content (fi/c), are the same as in [3]. The main variation parameter was the admixture dosage. Table 4.6 shows the project parameters. For a complete overview of the project parameters, see appendix C.

The chosen variations for the admixture dosages are selected with the basis from fi/c=0.7 for w/c=0.79, and fi/c=0.51 for w/c=0.59. The admixture dosages are applicable for all the other filler contents.

Table 4.6: The project parameters for the main measurements with Velde fillers. The highlighted admixture dosages are used in this study. 'From 2015' indicates from [3], and 'From 2016' indicates from this study.

Water/cement (w/c)	**0.79**			**0.59**		
Filler content (fi/c)	0.65	0.7	0.75	0.46	0.51	0.56
Water/powder (w/p)	0.479	0.465	0.452	0.415	0.396	0.377
Admixture- % of ...	***Cement***		***Powder***	***Cement***		***Powder***
From 2015	0.3		**0.18**	0.5		**0.33**
From 2016, First run	0.43		**0.25**	0.38		**0.25**
From 2016, Second run	0.56		**0.33**	0.62		**0.41**

Table 4.7: Project parameters for the measurements with the Feiring Bruk fillers.

Water/cement (w/c)	**0.59**	
Filler content (fi/c)	0.46	0.56
Water/powder (w/p)	0.415	0.377
Admixture-% of powder	**0.41%**	

For the separate measurements, the Feiring Bruk fillers' crushing method's effect on the flow properties with respect to the filler's specific surface area (SSA). The project parameters are shown in Table 4.7.

4.3 The Sedigraph

Micromeritics SediGraph 5100 is a sedimentation machine to determine the PSD of any kind of particles. See Figure 4.1a. *It is based on particle sedimentation speed and equivalent Stokian diameter.*[2] Spherical shape is assumed in the Stoke's law. Moreover, the effect of the particle shape on the matrix seems to be of a low importance when controlling PSD accurately [2], as mentioned in Section 3.3.

The SediGraph determines the particle size from velocity measurements by applying Stokes' law under the known conditions of particle and liquid density, and dynamic viscosity.

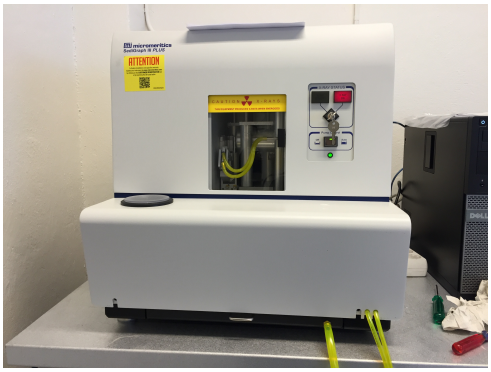
$$R = \sqrt{\frac{9\mu_d V}{2(\rho_p - \rho_f)g}}$$

Where μ_d is the dynamic viscosity (kg/m*s), V is the flow settling velocity (m/s), g is the gravitational acceleration (9.8 m/s^2), ρ_p is the mass density of the particles (kg/m^3) and ρ_f is the mass density of the liquid medium (kg/m^3).

It uses X-rays to measure the relative mass concentration of particles in the baseline liquid to determine particle size from 0.1 to 300 μm.[18] *Due to the limited sample size for analysis (for this study: 4.0-5.0 gr) in the instrument, the usual practice for measurements is sieving off the coarsest particles $\geq$63 μm, and then combining these results with the sedimentation analysis of the finest particles.*[2]

Due to the edition of the SediGraph device, the limitation of the maximum diameter for the particle was 63 μm. Even if the manual states that the machine can register up to 300 μm, analysis show that it works best $\leq$ 63 μm. Anything above this might disturb the PSD, thus particles $\geq$ 63 μm were mechanically sieved away. However, as defined in Section 3.1, the fillers used in the rheological and FlowCyl measurements contain particles in the range of 0-125 μm. To get the complete PSD, a combination of the mechanically sieving and SediGraph results were put together. In addition, the minimum particle size is set to be 1.0 μm due to uncertainties related to the amount of particles $\leq$1.0 μm.

A SediGraph measurement is performed for all five fillers used in this study, including the intermediate filler from [3].



(a) The Sedigraph Machine

(b) Close-up of the analysis cell.

Figure 4.1: Sedigraph III PLUS, Micromeritics. Equipment for determining the particle size distribution.

4.3.1 The SediGraph Procedure

In order for the SediGraph-analysis to give reliable results, the parameters for the device, and how to run the procedure had to be established.

The SediGraph Procedure

1. The intensity of X-ray beams was set to normal.
2. The particle diameter range was set to 0.1-63 μm.
3. The temperature was set to 30 °C.
4. The filler and liquid density were set.
5. A chosen baseline/dispersant liquid was run through the machine to establish the intensity and the resistance of this liquid.
   - Chosen liquid: 0.20% Sodium Hexametaphosphate. Liquid viscosity: 0.8007 mPa*s, and liquid density: 0.9957 g/cm^3.
   - To reach the 0.20% solution, 4 grams of Sodium Hexametaphosphate flakes were dissolved in 2 liters of chemically de-ionized water. First it sat for an hour in a heating cabinet of 70 °C, followed by keeping the liquid in a closed container overnight in room temperature. Evaporated water in the heating cabinet was added.

6. The desired sample amount was mixed into 80 ml of the liquid in a beaker and dispersed by hand and using an ultra sonic bath (Metson 50) for 30 seconds.

   – First, the particles were mixed with 60 ml of the 0.20% solution, by hand and ultra sonic bath, and then poured into the mixing chamber. To get the left-over particles in the beaker, 20 ml more of the liquid was poured into the beaker, hand mixed, and added to the mixing chamber. The second run with the 20 ml did not undergo the ultra sonic bath.

   – Due to some of the particles that had settled in the bottom of the beaker, after the ultra sonic bath, hand mixing was performed to completely disperse the mixture.

   – The 0.20% solution was poured into the beaker after the sample was measured. This indicates that the actual liquid volume was less than 80 ml. See correct amounts together with the sample's mass-% and volume fractions, in Table 4.8.

7. This homogeneous mixture was then sent through the machine to establish its X-ray intensity compared to the baseline liquid. The analysis time was about 2 hours for the chosen liquid. The major part of the analysis time focuses on the particles $\leq$1.0 μm.

Table 4.8: Mass-% and volume fraction for the samples used in the SediGraph-measurements.

	Velde	**Feiring Bruk**	**Units**
Liquid + mass volume	80	80	[cm^3]
Used mass amount	5.0	4.5	[gr]
Mass density	2.64	2.84	[gr/cm^3]
Volumetric mass amount	1.89	1.58	[cm^3]
Actual liquid amount	78.11	78.42	[cm^3]
Mass/total volume	2.37	1.98	[%]

To ensure that the concentration level was appropriate to run the analysis, there had to be a certain reduction from the intensity values for the baseline liquid to the solution of baseline liquid with particles. From the manual [19]: *If reduction is between 30 and 75%, Good is displayed. This indicates that the concentration level is appropriate.* The higher the intensity counts, the clearer the liquid. When particles are added, the intensity counts decrease. See example of the reduction intensities, in Table 4.9.

Table 4.9: Intensity reduction for the different fillers.

	Fillers	**Baseline liquid X-ray counts [kCnts/s]**	**Full scale liquid+particles X-ray counts [kCnts/s]**	**Intensity reduction [%]**
Velde	**Fine**	138	89	35.5
	Intermediate (2015)	138	90	34.8
	Intermediate (2016)	138	90	34.8
	Coarse	138	90	34.8
Feiring Bruk	**Primary subbus**	138	81	41.3
	0/2	138	87	37.0

The recording of X-ray intensity takes place in the analysis cell of the SediGraph, see Figure 4.1b. Up until the X-ray intensity starts monitoring, the mixture is kept in motion in order for the particles not to settle. During the sedimentation process, the largest particles are first to fall below the measuring level, and each mass measurement represents the cumulative mass fraction of the remaining fine particles. Gradually, finer and finer particles settle down and clear the measuring zone of the suspended particles and allowing the X-ray beams to once again pass through the cell uninterrupted.

Notice for future users of the SediGraph device

When using the SediGraph device, be aware of the limitations of the device, and the many parameters that have to be correct in order to utilize the results.

The analysis was run several times with each of the fillers under different circumstances. The results were different every time. As shown in Figure 4.2, for Velde's coarse filler, the first run was with the particle diameter range of 0.1-125 μm and Isopropanol (Liquid viscosity: 1.799 mPa*s, and liquid density: 0.7772 g/cm^3) as the dispersant liquid. Analysis time was about 4 hours. The graph seemed to indicate that $\geq$20% of the particles have a diameter less than 0.1 μm, which is highly unlikely. This would severely effect the SSA. After learning the limitations of the SediGraph, the maximum diameter for particles was 63 μm, particles above were sieved away to stop the disturbance with the generating of the PSD.

After the particles $\geq$ 63 μm were mechanically sieved away, a new analysis with the Isopropanol and the diameter range of 0.9-63 μm (to shorten the analysis time) was run. The results of this second trial is also displayed in Figure 4.2. Here the analysis indicates the PSD to have a steep curve in the range of 20-50 μm, which is incorrect to the reality.

For the third trial a different dispersant liquid was used to see how it would affect the results, 0.20% Sodium Hexametaphosphate was chosen. This liquid has a viscosity of under half of what the Isopropanol has, 0.8007 mPa*s, which indicated that the particles would settle more rapidly, half the total analysis time. As seen in Figure 4.2, this graph looks more accurate.

Do not trust the results blindly. Compare the results for the testing material with reference graphs of a reliable analysis. Run the test several times on the same material to be sure the results are reasonable and reliable.

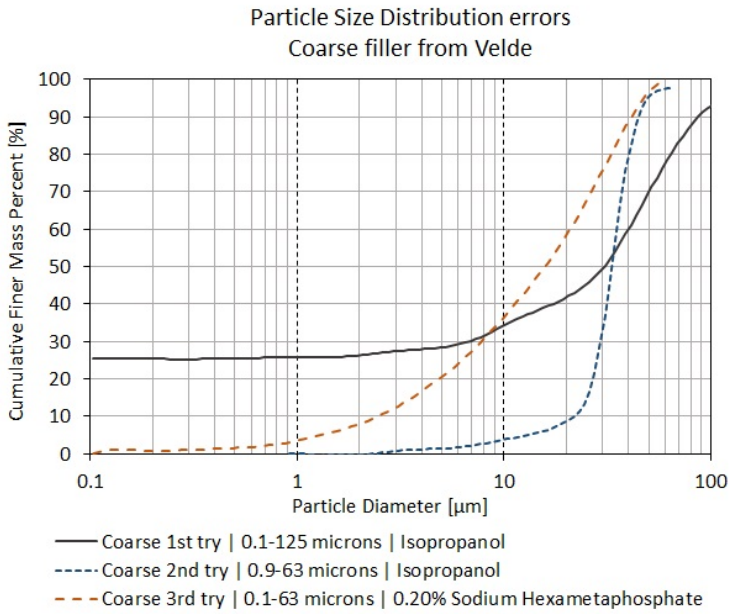


Figure 4.2: Example of SediGraph results. The filler displayed is the coarse filler from Velde, with the parameters listed pr. graph.

4.4 Mixing Procedure

The explanation of the mixing procedure is collected from [1, 2, 3]. Exact times of the mixing procedure is shown in Table 4.10.

The mixing of the matrices happened in a specific order and procedure to obtain the best and the most stable mixture. The mixing procedure for this study is of the same type as for [1, 3]. The matrix recipe resulted in a volume just above 2 liters, due to a water addition and a slightly increased admixture dosage. The 2 liter-volume was set in order to fit the amount in the cylindrical plastic container.

The cement was poured into the slightly moistened mixing bowl first because it had the highest density and finest grading, then fillers from fine to coarse were added. The cement and the fillers were first dry pre-mixed in a conventional Hobart mixer (model N-50, Hobart Manufactoring Company), then followed by addition of water and admixture during a period of 30 seconds. See the setup of the mixing area in Figure 4.3a. The wet-mixing was in two parts: one minute in the Hobart mixer, then a sequence of drill-mixing with two speeds. The drill mixing took place in a cylindrical plastic container (inner diameter of 11 cm and inner height of 29.7 cm) with a lid,

see Figure 4.3b, to ensure no spilling during the mixing [2]. After the drill-mixing, the matrix was poured into a plastic bottle and transferred to the FlowCyl and mini-slump spread area. When those two measurements were performed, a small amount of matrix was poured back into the plastic bottle and transferred down to SINTEF's concrete laboratory, where the rheometer measurements were performed.

(a) The mixing area with the Hobart mixer. **(b)** The equipment for the drill-mixing

Figure 4.3: Equipment and set-up for the mixing of the matrix.

Table 4.10: Mixing procedure obtained from [1]

Step nr:	**Time [min]**			**The process**
	Duration of each step	**Initial time on the watch**	**Time from when water is added**	
1	2	0	-2	Cement and fillers are pre-mixed at speed 1 on the Hobart-mixer (low = 140 rpm)
2	1	2	0	Water and admixtures mixed into the dry mix at speed 1 on the Hobart-mixer (low = 140 rpm)
3	0.5	3	1	Mixed matrix transferred over to a plastic container for drill mixing
4	2	3.5	1.5	Drill mixing at high speed (1850 rpm)
5	2	5.5	3.5	Rest
6	2	7.5	5.5	Drill mixing at moderate speed (1000rpm)
7	2.5	9.5	7.5	Rest. Matrix poured into a plastic bottle and transported over to the FlowCyl station
8	-	12	10*	Start of rheological measurements

*The FlowCyl-measurements were performed 10 minutes after water addition followed by mini-slump spread 1-2 minutes after the FlowCyl. The final measuring were the rheological measurements 6-9 minutes after the FlowCyl.

4.5 Rheological Measurements

The rheological measurements are the same as performed in [2], the description is collected from [2] as well. The measurements were performed on the fresh matrix mix right after the mixing procedure, Table 4.10. The order of the measurements were FlowCyl (10 minutes after water addition), mini-slump spread (1-2 minutes after the FlowCyl) and rheometer measurements (6-9 minutes after the FlowCyl).

4.5.1 FlowCyl Measurements

The explanation of the FlowCyl-apparatus and the approach used for the measurements are collected from [2, 3] . A FlowCyl-apparatus consists of a vertical cylindrical steel pipe with the length of 300 mm, at the end of the pipe there is a cone with a narrow nozzle outlet with a length of 100 mm. The nozzle outlet has an inner diameter of 8 mm, while the steel pipe has an inner diameter of 80 mm. See Figure 4.4. The FlowCyl-apparatus was placed in a rack with a steel bowl on an electronic scale connected to a computer. The computer records the matrix' flow rate every 2 seconds. A more detailed explanation is in [6, 14].

After finishing the matrix-mixing the mixture was transferred to the area where the FlowCyl and mini-slump spread measurements were performed. The FlowCyl measuring was performed exactly 10 minutes after water addition. The vertical cylinder was filled with the matrix up to a certain level, while a finger blocked the opening of the nozzle. The computer had a natural delay, so the finger was removed within two seconds of initiating the recording. The FlowCyl data were transferred to a matrix-plan-excel sheet [15], which calculate the flow resistance, λ_q, by using the flow rate.

Figure 4.4: The FlowCyl-apparatus during the measurements.

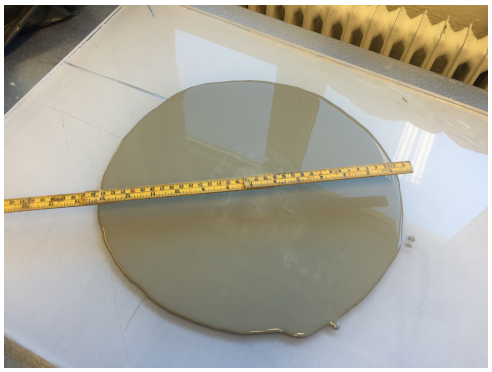
4.5.2 Mini-Slump Spread Measurements

The explanation of how the mini-slump spread measurements were performed, is copied from [2].

The mini-slump spread test was similar to the standardised slump cone tests used for concrete on a larger scale. The mini-cone used was of a top diameter = 39 mm, bottom diameter = 89 mm and height = 73 mm, see Figure 4.5a. *A smooth new plexiglass plate was used as the base for the measurements. The plate avoided water or very fluid matrix leakage under the mini-cone. During a measurement, the mini-cone was placed in the centre of the base plate and filled with fresh matrix.*[2] The matrix at the top of the cone was made level by itself due to it being highly flowable.

Subsequently the cone was gently lifted and the diameter of the matrix form was recorded to the closest 0.1 mm in two orthogonal directions when the flow had stopped, see example in Figure 4.5b. *The mini-slump spread value was then calculated as the mean of the two measured diameters.*[2] *The slump test will continue to flow as long as the stress due to gravity surpasses the yield shear stress, τ_0, and the plastic viscosity, μ, will mainly affect the velocity of the collapsing cone.*[7]

(a) Mini-slump spread cone



(b) Mini-slump spread

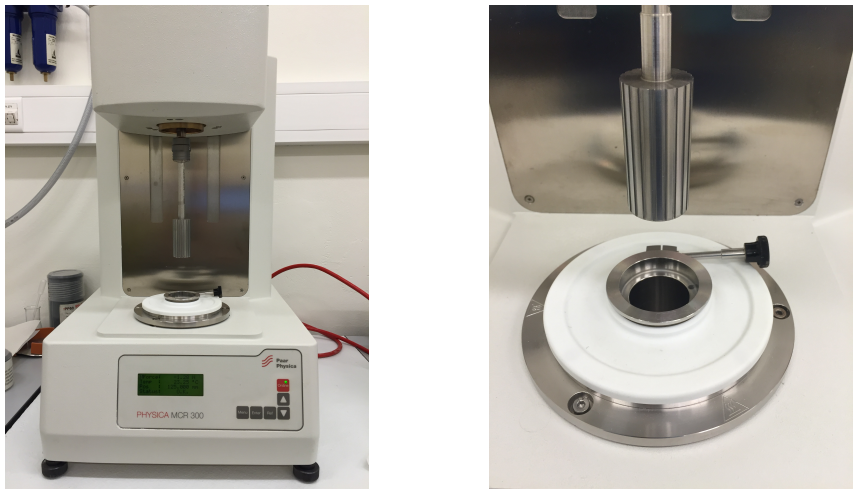
Figure 4.5: Equipment and result in the mini-slump spread measurement

4.5.3 Rheometer Measurements

The explanation of the instrument and the computer program is copied from [2]. The machine measures the plastic viscosity, μ, and the yield shear stress, τ_0, of the matrix.

Measurements were performed by a Physica MCR 300 rheometer (Anton Paar), Figure 4.6a, *equipped with a bob-in-a-cup geometry* Figure 4.6b. *The bob was of a flat bottom type, profiled to avoid slippage, of an outer diameter Di = 24.580 mm and gap length L = 50.000 mm. The inner diameter of the cup was De = 28.901 mm. The gap at the bottom of the bob was set to zero millimeters. The geometry then resulted in a tested sample volume of 10-11 ml. During the measurements the temperature of the sample was kept constant at* $20^o C$ *by a Peltier cooling module attached to the cup.*

During a measurement, the matrix was first homogenized for 30 sec at a shear rate of 60 s^{-1} *and then allowed to rest for another 30 sec. Thereafter, it was subjected to linearly increased shear rates from 1.0* s^{-1} *to 60* s^{-1} *over a period of 3 min (30 steps of 6 sec), followed by a step down of shearing from 60* s^{-1} *to 1* s^{-1} *for a further 3 min. The slope of the down-curve (decreasing shear rate) was used to calculate the Bingham's plastic viscosity,* μ*, while the intercept at zero shear rate was used to calculate the Bingham's yield stress,* τ_0*.*[2]



(a) Physica, rheometer machine **(b)** Bob-in-cup

Figure 4.6: Physica MCR 300 rheometer (Anton Paar), and the bob-in-cup setup.

Chapter 5
Results and Discussion

5.1 The Particle Grading

The particle size distribution (PSD) from each of the fillers is obtained by combining mechanical sieving and SediGraph analysis. The combination is important due to the SediGraph giving best results when the maximum particle size it registers is 63 μm, and to get an estimate of the particle sizes ≥ 63 μm, mechanical sieving is performed, as previously discussed in Section 4.3. The transition between the sieving and the SediGraph values will have a distinct break in the PSD curve, due to the different grading procedures.

Discussing the effect of the grading on the FlowCyl-results, the complete 0-125 μm grading must be considered. The finest particles constitute the major part of the specific surface, but the relative portion of fine particles in the filler depend on the complete grading.

For the PSDs and additional frequency curves for each of the fillers, both from Velde and Feiring Bruk, are in appendix D.

5.1.1 The Basic Fillers from Velde

Figure 5.1 shows the PSD for each of the basic fillers from Velde, retrieved from the SediGraph analysis. The range of the PSD is from 0.1-63 μm. When considering only this range, all three fillers look particularly similar. The coarse filler even looks like it contains the most content of finer particles, which is peculiar. If only these results from the SediGraph are used, the perception of the reality can be mistaken. The grading of the particle sizes are similar because they all have the same producer. However, to get the entire PSD of the different fillers, the relative portion of the fine particles in the filler has to be taken into consideration. The relative portion is how much of the filler combination that is concentrated ≤ 63 μm. To find this amount, a mechanical sieving was performed.

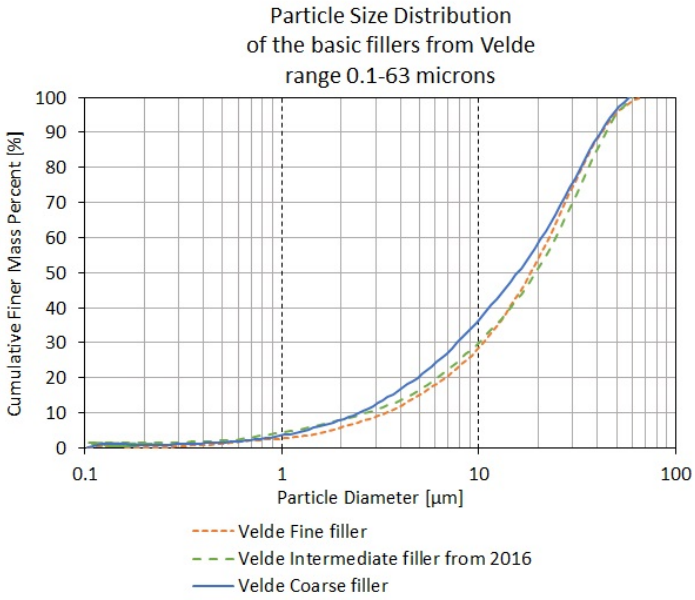


Figure 5.1: The SediGraph results of the basic fillers from Velde, used in 2016 (this study). Range 0.1-63 μm.

When combining the two procedures of particle grading, the results look as displayed in Figure 5.2. The PSD's for the basic fillers show a considerable and logical difference between them. This shows how important it is to combine both the mechanical sieving and the SediGraph results to get a good perception of the PSD. The ranking of the fillers goes from finest (the fine filler), through the intermediate filler and to the coarse filler that contains the least content of fine particles. This is consistent with what the producer has promised to deliver.

What also is shown is that the intermediate filler from 2015 ([3]), is very close to the coarse filler. The coarse filler contains even higher amounts of fines than the intermediate one. This is a peculiar case, but will not be further discussed.

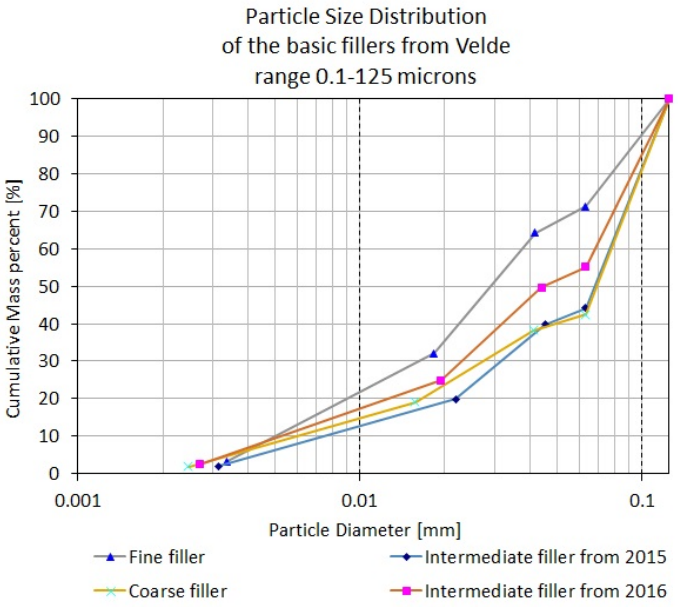


Figure 5.2: The mechanical sieving and SediGraph Analysis. The difference in the fillers from Velde, including the intermediate filler from 2015 ([3]).

5.1.2 The Differences in Intermediate Fillers from Velde

The SediGraph analysis' of the two intermediate fillers from Velde, from 2015 ([3]) and from 2016 (this study), are viewed in Figure 5.3. In this figure, the gradings look almost identical. From this distribution, there is no need for speculation about whether or not they are the same filler. But as mentioned in Section 5.1.1, the SediGraph results cannot be trusted alone. The knowledge of the relative portion of the finer particles in each filler is important. A combination of the mechanical sieving and the SediGraph results, is displayed in Figure 5.4.

In Figure 5.4 it is apparent that the intermediate filler from 2016 has a higher content of fine particles compared to the intermediate filler from 2015. This difference would not have been detected if the two grading procedures were not combined. The difference in the relative portion of fines could be due to the different moisture content in the sand mixtures received from Velde in 2015 and in 2016, (Section 4.1.1).

The effect of the finer particle size distribution (PSD) for the 2016 intermediate filler, will show in the flow resistance, λ_q, results. The higher content of fine particles result in a more viscous matrix, and thus higher flow resistance than in [3].

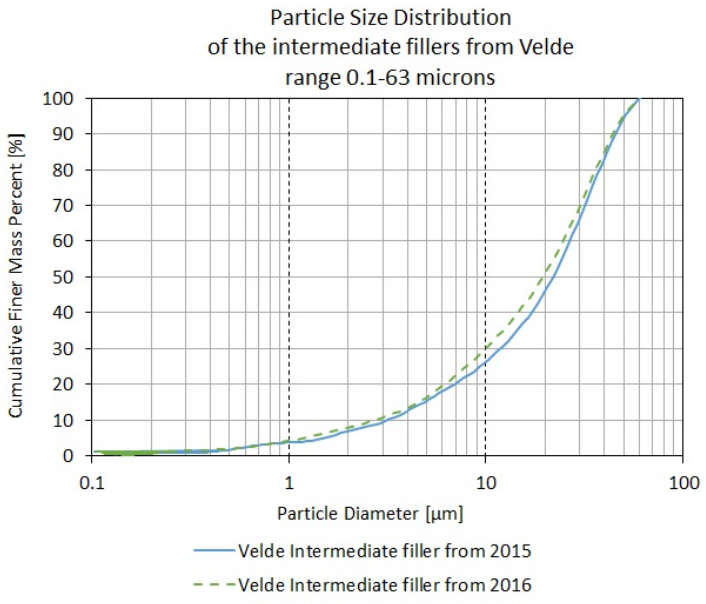


Figure 5.3: The SediGraph results for the difference in the intermediate fillers from Velde, from 2015 ([3]) and from 2016 (this study).

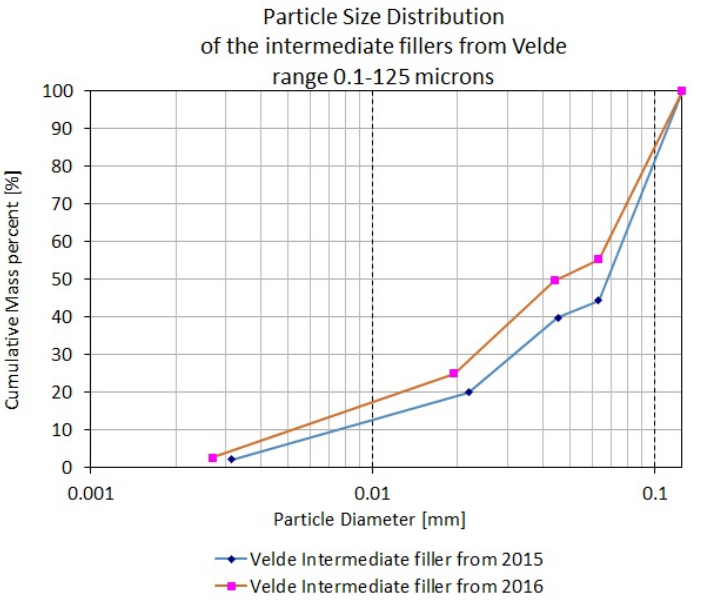


Figure 5.4: The mechanical sieving and SediGraph Analysis. The difference in the intermediate fillers from Velde, from 2015 ([3]) and from 2016 (this study).

5.1.3 Natural Differences in Particle Size Distributions (PSD)

Displayed in Figure 5.5, are particle size distributions (PSDs) from different sieving batches from Velde. The notations in the figure indicate that R1-R3 are from [1], and H1-H3 are from this study. As shown in the figure, "R1 - Fine filler" and "H1 - Fine filler" look similar enough to indicate that they are the same type of fillers. It is not sufficient to determine a filler solely based on the common name; 'fine', 'intermediate' and 'coarse'. As the Figure 5.5 shows, there are natural differences in the PSDs. This can be due to the moisture content, and different sand properties dependeding on the time and place the sand was excavated from the quarry. When receiving a filler, a PSD of the filler must be performed to distinguish any differences from batches received before. This is to determine if the same type of filler fraction (for instance the "fine filler") is comparable when it has been sieved at different times, even years apart.

The figure clarifies that the basic fillers used in this study, are similar to the ones used in [1], which make them comparable.

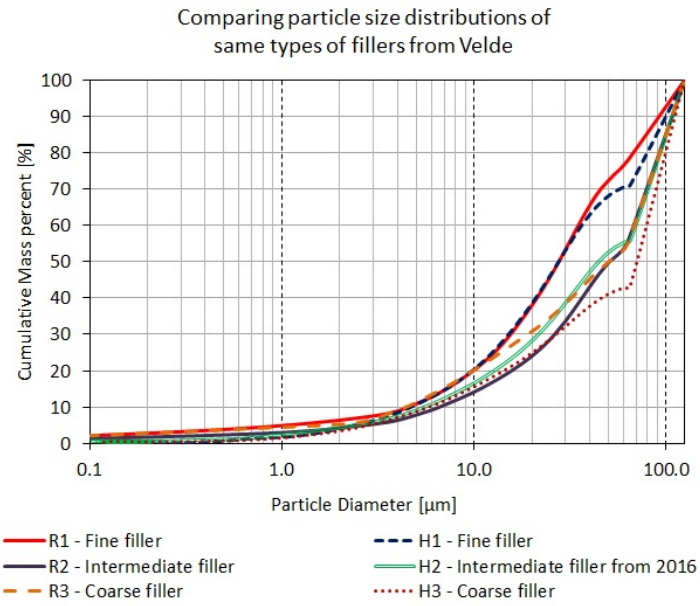


Figure 5.5: The mechanical sieving, SediGraph and PartAn Image Analysis. The differences in same types of fillers from Velde, for comparison. R1-R3 indicate PSD's from [1], while H1-H3 indicate PSD's from 2016 (this study).

5.1.4 The Specific Surface Area (SSA)

The calculation of the specific surface area (SSA) has previously been explained (Section 3.1.2). If judged by a visual interpretation of PSD, two fillers might appear to be very similar. However SSA approximations or measurements should be used to estimate whether their effect on the matrix and concrete flow properties will also be similar. To determine the SSAs for this study, a combination of mechanical sieving and SediGraph analysis is performed. The higher the SSA, the higher demand for cement, which from an economical and environmental point of view is unfortunate because of the high cost of cement, and the high CO_2-emission related to the cement production.

In Table 5.1, the SSAs of the Velde fillers are presented. Of these four fillers (fine, two intermediates, coarse), the fine filler, with the minimum particle size of 1.0 μm, seems to have the highest SSA, as presumed in Section 3.5. Having the highest SSA, indicates a higher content of fine particles. Between the intermediate filler from 2015 and 2016, the SSA for the latter one, has the highest SSA. This can be due to the 2016 intermediate filler being completely dry prior to the sieving (Section 4.1.1).

The variations in SSA will affect the flow properties, as it has before. The higher the SSA, the more viscous the matrix liquid, and thus the higher the flow resistance, λ_q.

Table 5.1: The specific surface areas of the basic fillers, found through the Sedigraph analysis. 2015 is from [3] and 2016 is from this study.

Specific surface area [1/mm] Velde fillers			
Minimum size [μm]		**1.0**	**10**
Fine		450	154
Intermediate	**2015**	280	114
	2016	357	126
Coarse		343	108

The method used to retrieve the PSD, thus the SSA, in [1] (Figure 3.6), was a PartAn Image Analysis. *Through the PartAn image analysis, results show that particles $\leq$10 μm appeared to be insignificant in the PSD determination* [20], which indicate that the SSA of the particles $\leq$10 μm are not included in the total SSA.

There has a major effect on the total SSA, when ending the registering of particle sizes at 10 μm. The magnitude of the effect, is viewed in Table 5.1. Take for instance the "fine"-filler from the SediGraph analysis; if the minimum particles size was chosen to be 10 μm, then (450-154)/450 * 100% = 66% of the total SSA would be missing. With results depending on the total SSA, prior to the measurements, the choice of PSD determination method and minimum particle size are extremely important to determine.

The methods used to find the PSDs for 2015 ([3]) in Figure 3.5 and for 2016 (this study) is the SediGraph analysis, and for Figure 3.6 it is the PartAn image analysis. These are two different methods, the comparison of the results in this study cannot be presented in the same graph as the one in Figure 3.6.

5.2 The Effect of Variation in Parameters on the Flow Properties

General for the following figures are that the admixture dosage is lower in the higher water/cement-ratio, w/c. The dosage variations are also lower, which concludes that the effect of variations become obviously lower for the measured properties. The effects will be shown for w/c=0.59 and 0.79. The different parameters are the filler content (fi/c), the water/powder-ratio (w/p) and the admixture dosage.

For a complete overview of the rheological results, see the table in appendix E

5.2.1 The Effect of the Variation in Filler Content and the Admixture Dosage on the Flow Resistance

For the w/c=0.59, Figure 5.6, with regards to the fi/c, and with the admixture dosage (0.25%/powder), there is a slightly higher increase in flow resistance from fi/c=0.51-0.56, than the minimal increase from fi/c=0.46-0.51. This could be due to either the filler content increase in the first case, exceeds a certain level of the particle concentration, which gives an exponential increase in the flow resistance. Or that over this certain level, with this w/c-ratio, the low admixture dosage becomes too low to restrain an increase of the flow resistance in the matrix.

As long as the w/c stays the same, then the w/p is directly related to the fi/c-ratio. Then it is obvious that the w/p effect is similar to the fi/c effect.

In terms of admixture dosage, increasing the dosage reduces the flow resistance to some extent. It seems that when increasing the dosage from 0.25 to 0.41%/powder, the flow resistances for the increased dosage become consistent in relation to each other, more than they were before addition of more admixture.

As for the w/c=0.79, Figure 5.7, with regards to the fi/c, and the admixture dosage (0.25%/powder), the flow resistance for the fi/c=0.70 is slightly higher than the other two filler contents, but higher nonetheless. The measurements with the admixture dosage of 0.25%/powder, are the redone measurements from [3] but with an admixture dosage increase from 0.18 to 0.25%/powder. This increase in admixture was obviously insufficient to remove this higher flow resistance in fi/c=0.70. This peak is probably due to a non-negligible yield shear stress that disturbes the flow resistance results. Other than that, it looks as though an increase in the filler content only slightly increases the flow resistance. This means that variation in the filler content does not affect the flow resistance that much. Same for the w/p-ratios, because of the fi/c and w/p relationship.

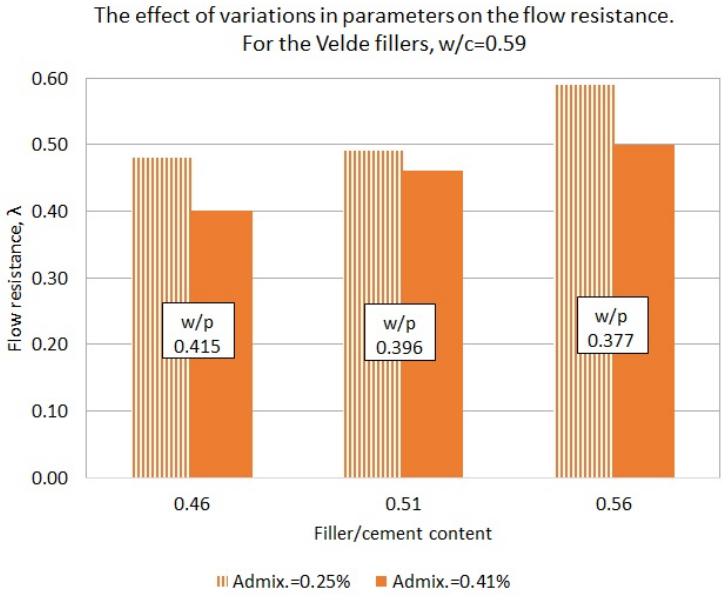


Figure 5.6: How the variation in filler content (filler/cement content), water/powder-ratio and admixture dosage (of total powder content) affect the flow resistance in the w/c=0.59 results.

As for the admixture dosage, when realizing the yield shear stress was still too high to be neglected for the admixture dosage of 0.25%/powder, then increasing the dosage from 0.25 to 0.33%/powder would make the flow resistance not disturbed. The flow resistance values go from peaking in the fi/c=0.70, to form a linear gradient from fi/c=0.65 to 0.75. The drops in the flow resistance are not too high, but that only indicates a small increase in the admixture dosage was needed to correct the disturbance from [3].

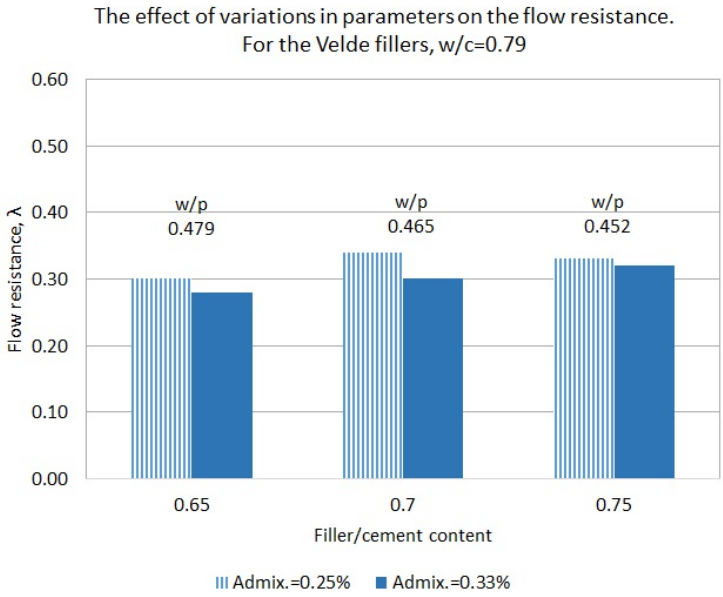


Figure 5.7: How the variation in filler content (filler/cement content), water/powder-ratio and admixture dosage (of total powder content) affect the flow resistance in the w/c=0.79 results.

5.2.2 The Effect of the Variation in Filler Content and the Admixture Dosage on the Yield Shear Stress

For the w/c=0.59, Figure 5.8, with regards to the fi/c, and the admixture dosage (0.25%/powder), there is a higher increase in yield shear stress, τ_0, from fi/c=0.51-0.56, than from fi/c=0.46-0.51. This could be due to the low admixture dosage just being able to restrain a high variation in the yield shear stress, in an increase of the filler content up to a certain level (here around fi/c=0.51). When exceeding this level of filler content, the low dosage is in fact too low to restrain an increase in the yield shear stress in the matrix. The same kind of effect goes for the w/p-ratio.

For the admixture dosage, it is apparent that an increase from 0.25 to 0.41%/powder reduces the yield shear stress drastically to a negligible level, where it will not disturb the flow properties in a mentionable way.

The yield shear stresses are higher than expected for the low admixture dosage of 0.25%/powder for w/c=0.59. While for the w/c=0.79 results, the yield shear stresses for admixture dosage of 0.25%/powder are much lower. However, it is the yield shear stresses in w/c=0.79 that disturb the flow resistance in Figure 5.7. That would mean

that even if the yield shear stresses are low for 0.25%/powder admixture dosage in w/c=0.79, they are too high to be neglected.

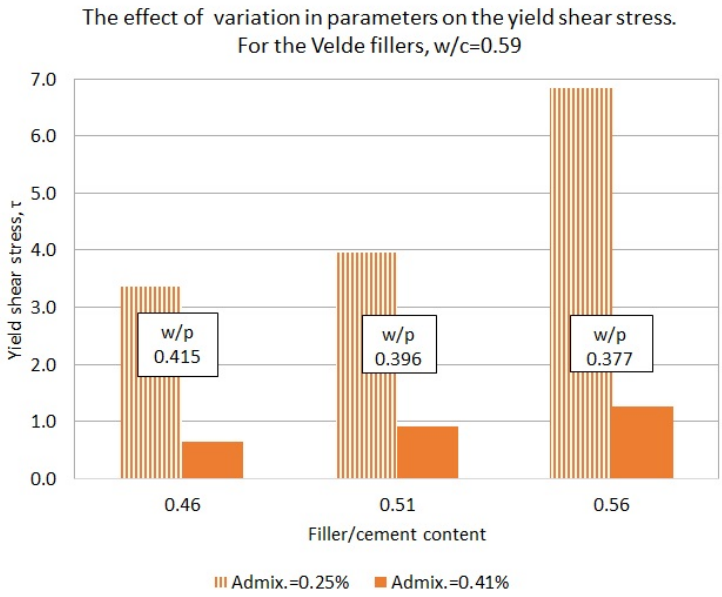


Figure 5.8: How the variation in filler content (filler/cement content), water/powder-ratio and admixture dosage (of total powder content) affect the yield shear stress in the w/c=0.59 results.

As for the w/c=0.79, Figure 5.9, with regards to the fi/c, and the admixture dosage=0.25%/powder, the increase in yield shear stress between the increasing filler contents are more or less consistent compared to the w/c=0.59-values.

The w/p-ratios behave similar, when they are decreasing; the yield shear stress consistently increases. Generally the yield shear stresses are much lower, in w/c=0.79, than for the w/c=0.59-values.

As for the admixture dosage increase, when increasing the dosage from 0.25 to 0.33%/powder, the yield shear stress drops down to the same negligible level as for the w/c=0.59-values. It seems that there is a threshold level for the admixture dosage that reduces the yield shear stress to a negligible level. The yield shear stress value for fi/c=0.70 and admixture dosage of 0.25%/powder is apparently high enough to interfere with the flow resistance, λ_q, in Figure 5.7, for the same matrix. Because of the peak in flow resistance for the fi/c=0.70-case, it is obvious that something is affecting it. By increasing the admixture dosage from 0.25 to 0.33%/powder, the

yield shear stress is halved, and the flow resistances go from a peak value for the fi/c=0.70-case, to a consistent linear rise.

For the yield shear stresses with the admixture amount=0.25%/powder in Figure 5.9, they increase slightly compared to one another. If the one for fi/c=0.70 is too high to not disturb the flow resistance, then perhaps the other two filler contents also are too high. But when the yield shear stress in the fi/c=0.70 case was reduced to an negligible level by increasing the admixture dosage, then it is appropriate to trust that the yield shear stresses for the other two filler contents are negligible as well.

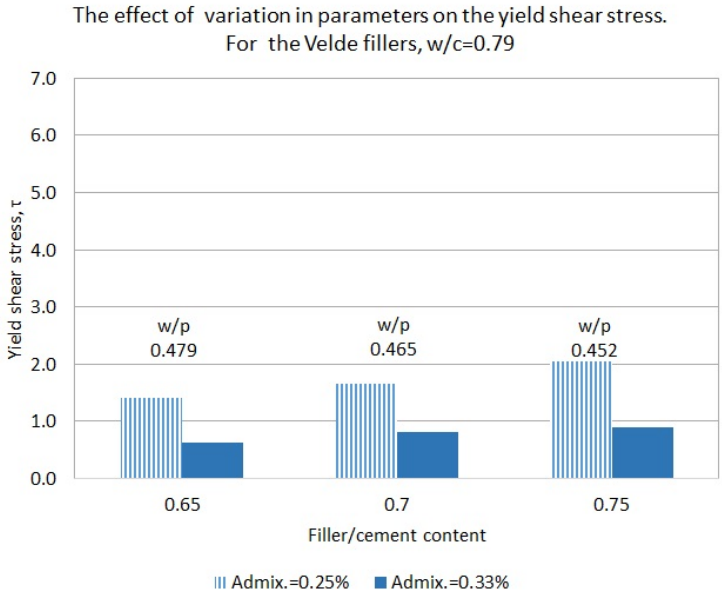


Figure 5.9: How the variation in filler content (filler/cement content), water/powder-ratio and admixture dosage (of total powder content) affect the yield shear stress in the w/c=0.79 results.

5.2.3 The Effect of the Variation in Filler Content and the Admixture Dosage on the Plastic Viscosity

For the w/c=0.59, Figure 5.10, with regards to the fi/c, and the admixture dosage (0.25%/powder), there is a higher increase in plastic viscosity from fi/c=0.51-0.56, than from fi/c=0.46-0.51. This could be due to the already mentioned reasons from the flow resistance, λ_q, and the yield shear stress, τ_0, that up to a certain level (here around fi/c=0.51), the low admixture dosage is just sufficient enough to withstand the increase in filler content and the decrease in w/p. But if this level of filler content is exceeded, the low dosage is too low to restrain an increase in the plastic viscosity in the matrix. This is same for the w/p-ratio.

In terms of admixture dosage, it is apparent that an increase from 0.25 to 0.41%/powder reduces the plastic viscosity to a rather low level, how does this work when the matrix's flow resistance is suppose to be closely related to the plastic viscosity? Apparently a reduction in plastic viscosity in the range that the w/c=0.59 show, does not affect the flow resistance that much.

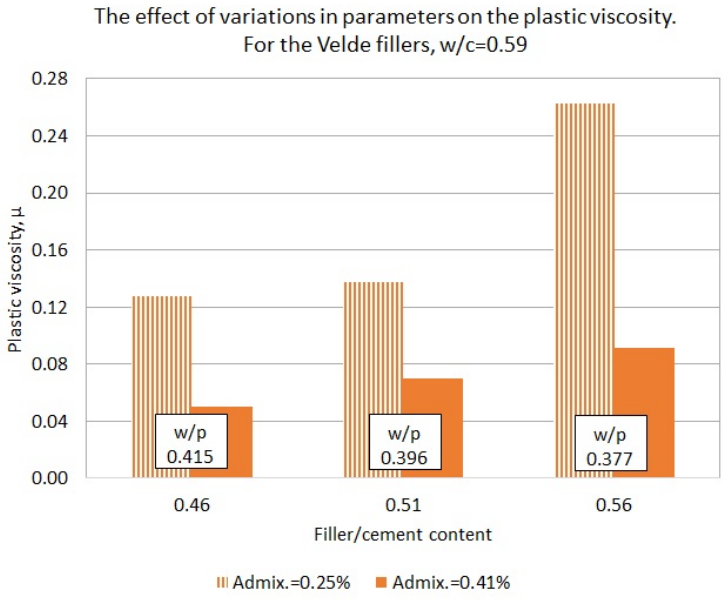


Figure 5.10: How the variation in filler content (filler/cement content), water/powder-ratio and admixture dosage (of total powder content) affect the plastic viscosity in the w/c=0.59 results.

For the w/c=0.79, Figure 5.11, with regards to the fi/c, and the admixture dosage=0.25%, the increase in plastic viscosity is minimal. The variation in the filler content does not affect too much, and neither does the variation in w/p. Between the w/c=0.59 and the 0.79 values with the admixture dosage of 0.25%/powder for both, differ the most compared to one another. The matrices with the increased dosage do not differ as much between the w/c=0.59 and the 0.79.

When the admixture dosage increases from 0.25 to 0.33%/powder in Figure 5.11, the plastic viscosity decreases slightly. There is not anything out of the ordinary about the effect of the different parameters on the plastic viscosity. It behaves as expected.

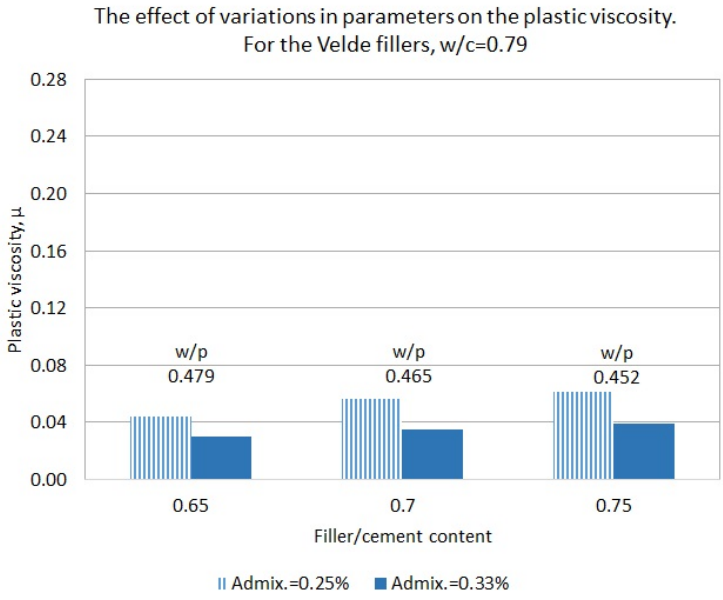


Figure 5.11: How the variation in filler content (filler/cement content), water/powder-ratio and admixture dosage (of total powder content) affect the plastic viscosity in the w/c=0.79 results.

5.2.4 The Effect of the Variation in Filler Content and the Admixture Dosage on the Mini-Slump Spread

For the w/c=0.59, Figure 5.12, with regards to the fi/c, and the admixture dosage (0.25%/powder), the higher the filler content, the lower the mini-slump spread. With an increase in filler content, this means an increase in the amount of particles and therefore an increase in the internal forces acting on each other. The reduction in the mini-slump spread, by increasing the filler content, is an predicted effect. It also seems that here, for the low admixture dosage, the mini-slump spread is not too affected by the filler content increase up to this previously discussed certain level, but when exceeding this level, the effect on the amount of particles is larger than the low admixture dosage can handle. For the w/p effect it is a similar explanation as for the fi/c variations.

For the admixture dosage, increasing the dosage increases the mini-slump spread. It makes the values more linearly consistent in the increasing filler content. It seems the results here are more clear in the case of the admixture dosage being 0.41%/powder, than for the 0.25%/powder case.

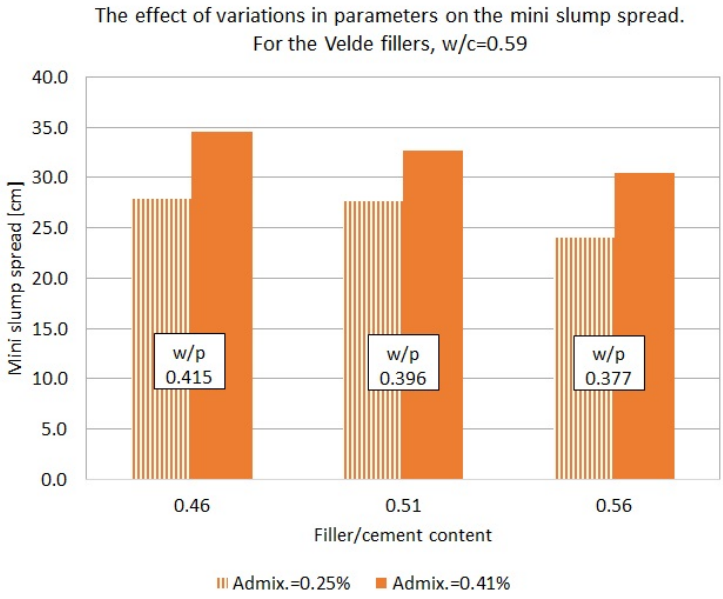


Figure 5.12: How the variation in filler content (filler/cement content), water/powder-ratio and admixture dosage (of total powder content) affect the mini-slump spread in the w/c=0.59 results.

As for the w/c=0.79, Figure 5.13, with regards to the fi/c, and the admixture dosage=0.25%/powder, the mini-slump spread decrease slightly when increasing the filler content. It does not seem that when exceeding the certain level of filler content, as previously discussed, disturbs the mini-slump spread, like it did for the w/c=0.59 values.

This is also true for the w/p-ratios. For w/c=0.79, there does not seem to be a certain minimum water content to pay attention to, as it has for other parameter values.

As for the admixture dosage increase, when increasing the dosage from 0.25 to 0.33%/powder, the mini-slump spread increase slightly. The small variation can be due to sufficient water content for the admixture to work with, for both admixture dosages. The admixture increase affects the mini-slump spread in a lower extent than for the w/c=0.79 cases.

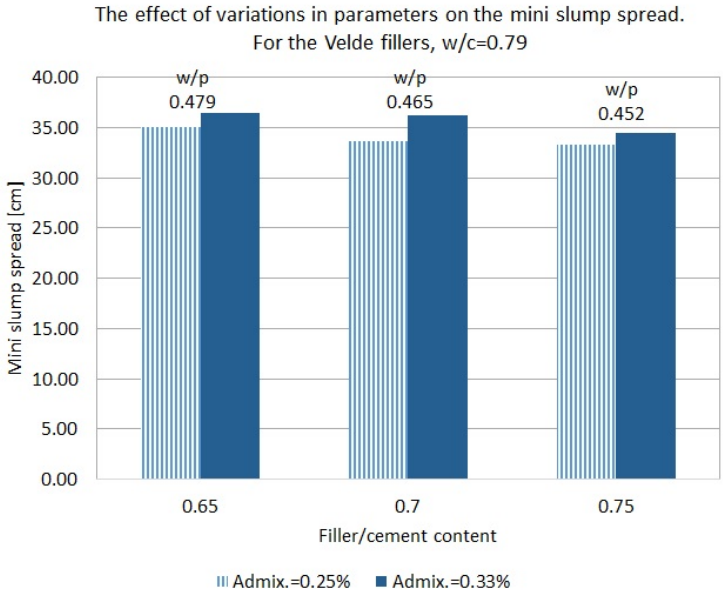


Figure 5.13: How the variation in filler content (filler/cement content), water/powder-ratio and admixture dosage (of total powder content) affect the mini-slump spread in the w/c=0.79 results.

5.2.5 The Relation Between the Four Parameters

It seems when the admixture dosage is increased, all the parameters either drop to a negligible level (for the yield shear stress, τ_0), to a lower level (for the flow resistance, λ_q, and plastic viscosity, μ), or increase slightly (for the mini-slump spread), as expected.

The effect of increased admixture dosage seems to be higher for the yield shear stress and the plastic viscosity, than for the flow resistance and the mini-slump spread.

For the effects between the w/c's, there is in general a higher difference between the admixture dosages in the low w/c, than for the high w/c. This can be due to either a higher particle concentration generating more forces, or the increase in admixture dosage is higher for the w/c=0.59 than for the w/c=0.79. When the admixture dosage increase is higher, then obviously the effect of variations will be higher for the measured properties. A clear effect on the variation of w/c's cannot be established here.

The effect of the filler content increase affects the flow resistance, the yield shear stress and the plastic viscosity in a larger extent, than the mini-slump spread, in the w/c=0.59, when exceeding the fi/c=0.51. Generally throughout the figures, the values either increase or decrease consistently, relative to what is measured and how the parameters vary, expect for the flow resistance in the fi/c=0.70, admixture dosage of 0.25%/powder for the w/c=0.79 case. However, what is the reason for the fi/c=0.70's flow resistance to become slightly higher than the flow resistance for the fi/c=0.75's case? The theory states that the higher the filler content, thus the particle concentration in the matrix, the higher the flow resistance will be; this does not seem to come true in this case. The reason is unclear.

The w/p's behavior is similar to the filler content behavior because within the same w/c-ratio, w/p is directly related to the fi/c.

The overall yield shear stress values in Figure 5.9, with the low admixture dosage (0.25%/powder) are in the same low area of the yield shear stress values in Figure 5.8, for the matrices with increased admixture dosage (0.41%/powder). When the yield shear stress is low for both those cases, why is there a larger difference in the same cases for the flow resistance, Figure 5.6 and Figure 5.7, and a smaller difference for the plastic viscosity, Figure 5.10 and Figure 5.11? Should there not be a direct link between them? The Bingham model may not be as accurate in defining these relationships as desired. A more precise model would be better in more clearly defining the relationships between the fundamental and the measured properties, like FlowCyl and mini-slump spread. The flow progress in the FlowCyl and the rheometer is not laminar, the tendency for cohesiveness between the matrix and

the steel in both the measuring apparatus can probably influence the results. This cohesiveness is probably affected by the admixture dosage as well. It seems that the flow resistance is more sensitive to variations in w/c, fi/c, and w/p, than the plastic viscosity. It is apparent that the yield shear stress affects the flow resistance to a larger extent than the plastic viscosity.

5.3 The Rheological Relationships

5.3.1 The Bingham Relationship

The Figure 5.14 shows how the yield shear stress, τ_0, and the plastic viscosity, μ, behave when the matrices are mixed with sufficient admixture dosages, where neglecting the yield shear stress is assumed. In [3], this is the behavior desired for all the matrices, where the main purpose was to look at variations of the water/powder-ratio (w/p), with a consistent admixture dosage. However, because the admixture dosage was set too low (0.18%/powder) in [3], there were disturbances in the results, probably caused by the yield shear stress, which concluded that the admixture dosage was too low to neglect the yield shear stress.

Comparing the Figure 5.14 results with the Bingham relationship in Figure 3.3, it is obvious that the yield shear stress in these results has been reduced to a negligible level, and only variations in the w/p-ratio varies the plastic viscosity. This indicates that the matrices with the sufficient dosages behave as a Bingham fluid, closely related to the plastic viscosity and a yield shear stress that has reached a negligible level. Related flow resistances to the plastic viscosity in Table 5.2.

Table 5.2: The flow resistances related to the plastic viscosity's with sufficient admixture dosages from Figure 5.14.

	Filler content fi/c	**Plastic viscosity, μ**	**Flow resistance, λ_q**
w/c 0.79	0.65	0.030	0.28
	0.70	0.035	0.30
	0.75	0.039	0.32
w/c 0.59	0.46	0.050	0.40
	0.51	0.070	0.46
	0.56	0.091	0.50

In Figure 5.15, the behavior between the yield shear stress, τ_0, and the plastic viscosity, μ, are displayed for all admixture dosages, both the sufficient and the insufficient.

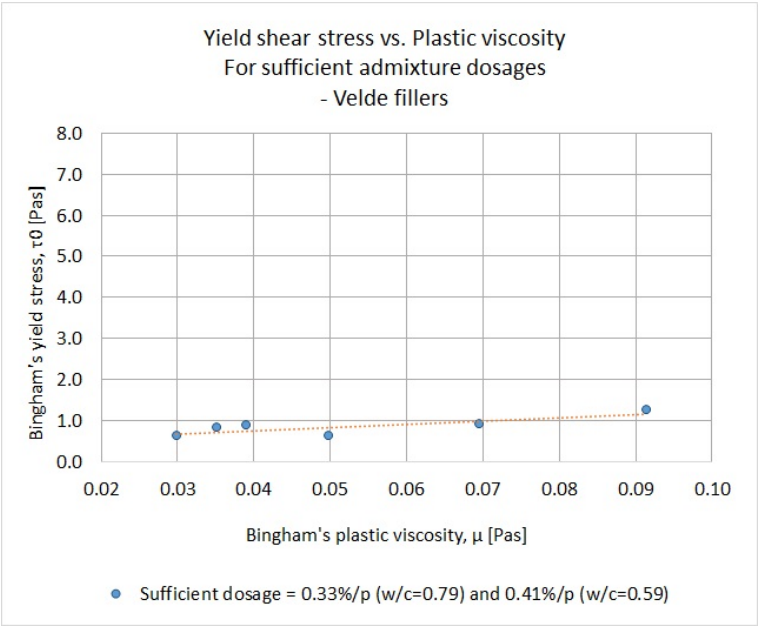


Figure 5.14: How the yield shear stress and the plastic viscosity behave when the admixture dosages are sufficient: 0.33%/powder (w/c=0.79) and 0.41%/powder (w/c=0.59)

When the results from Figure 5.15 are compared to Figure 5.14, it is apparent that most of the results have too low admixture dosage to neglect the high yield shear stress. Due to the high yield shear stress, the matrices are not solely related to the plastic viscosity, but is also affected by the yield shear stress. The variation of yield shear stress for the results in Figure 5.15, is due to the variation in the admixture dosages. This is a clear example of how this works.

As mentioned previously in Section 5.2.2 for the w/c=0.79, there seems to be a threshold level for the admixture dosage that reduces the yield shear stress to a negligible level. What this threshold level is, depends on the w/c, the w/p, and the fi/c.

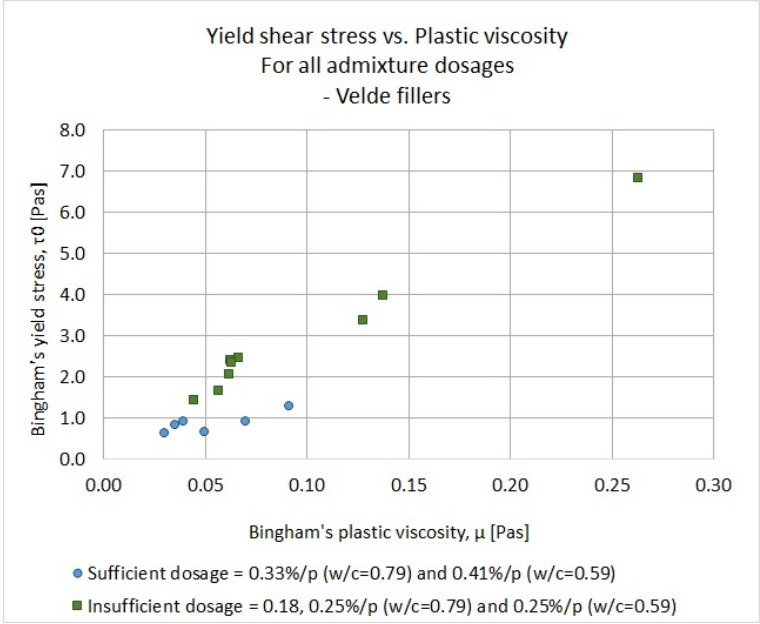


Figure 5.15: How the yield shear stress and the plastic viscosity behave when all the admixture dosages are included: 0.18, 0.25, 0.33%/powder (w/c=0.79) and 0.33, 0.41%/powder (w/c=0.59)

5.3.2 Additional Relationships

Additional relationships between the affected parameters are presented, with the knowledge of how they theoretically should behave.

Flow resistance, λ_q, plastic viscosity, μ, and mini-slump spread correlate well, and describe similar relationships.

Flow Resistance and Plastic Viscosity

As mentioned in Section 3.2 about 'A Bingham fluid', the matrix's flow resistance, λ_q, will be primarily related to the matrix's plastic viscosity, μ, and less affected by small variations in the yield shear stress, τ_0. This was the assumed outcome with the sufficient admixture dosage.

In Figure 5.16, the results with the sufficient admixture dosages the make the yield shear stress negligible are displayed. There is a clear indication of the flow resistances relates to the plastic viscosity. When the plastic viscosity increases, as does the flow resistance.

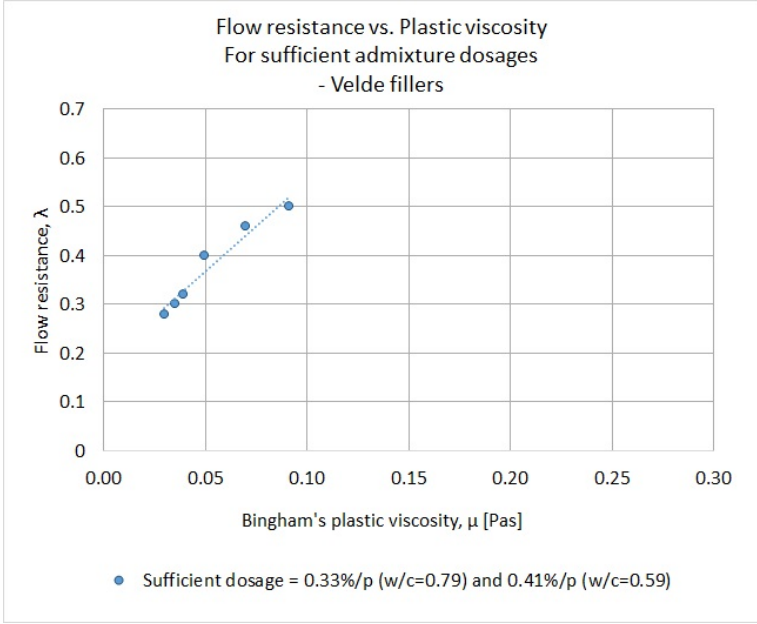


Figure 5.16: How the flow resistance and plastic viscosity relationship behave when the admixture dosages are sufficient: 0.33%/powder (w/c=0.79) and 0.41%/powder (w/c=0.59)

Figure 5.17, on the other hand, has results with all the admixture dosages. The tendency line reveals that matrices with insufficient admixture dosages, and their scattered results, disturb the clear relationship between the flow resistance and the plastic viscosity. This is unfortunate.

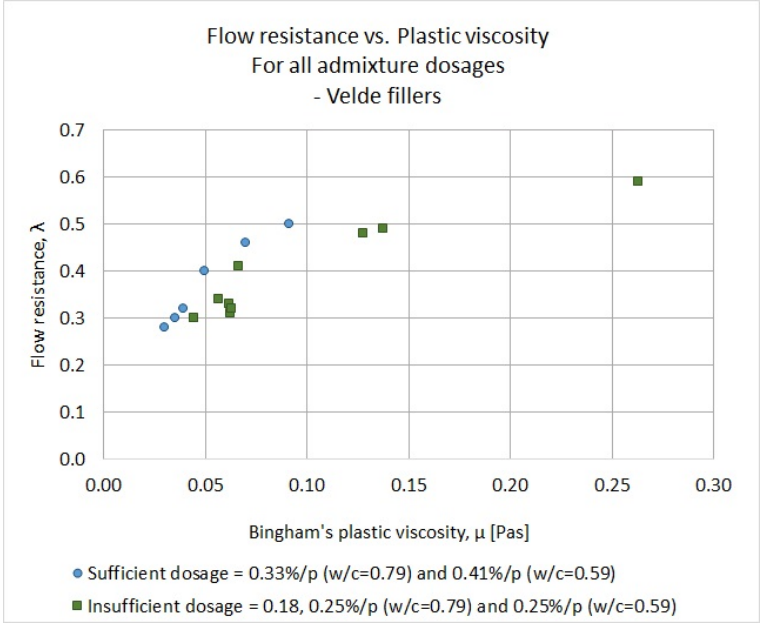


Figure 5.17: How the flow resistance and plastic viscosity relationship behave when all the admixture dosages are included: 0.18, 0.25, 0.33%/powder (w/c=0.79) and 0.33, 0.41%/powder (w/c=0.59)

Mini-Slump Spread and Plastic Viscosity

In Section 3.2 about 'A Bingham fluid', states that the matrix's plastic viscosity, μ, behavior is determined through the mini-slump spread measurement. This indicates that their relationship should be clear. In Figure 5.18, results with all the admixture dosages are included. Even with both the sufficient and the insufficient dosages the relationship is clear. It is apparent that this relationship holds through any admixture dosage.

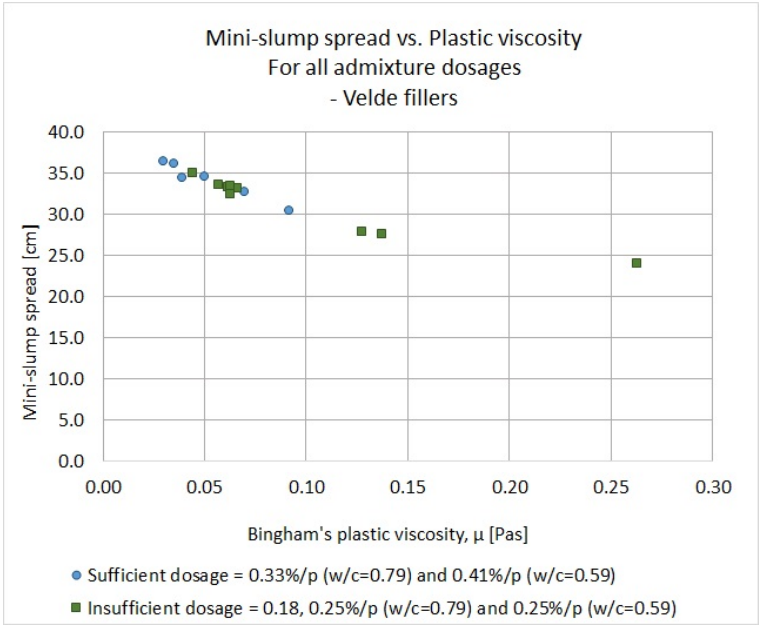


Figure 5.18: How the mini-slump spread and plastic viscosity relationship behave when all the admixture dosages are included: 0.18, 0.25, 0.33%/powder (w/c=0.79) and 0.33, 0.41%/powder (w/c=0.59)

Mini-Slump Spread and Yield Shear Stress

In Section 3.2 about 'A Bingham fluid', defines the method to determine matrix's yield shear stress, τ_0, to be the mini-slump spread together with results from the rheometer machine (see Section 4.5.3).

The mini-slump spread and the yield shear stress are not supposed to have a distinct linear relationship. However, from the results in Figure 5.19, it can look that way, in an indirect, scattered matter. The behavior between them is supposed to look like the results with the sufficient admixture dosage, viewed in Figure 5.19. Because of the addition of the insufficient dosages, for future measurements, if this behavior happens again, it is apparent what the reason could be.

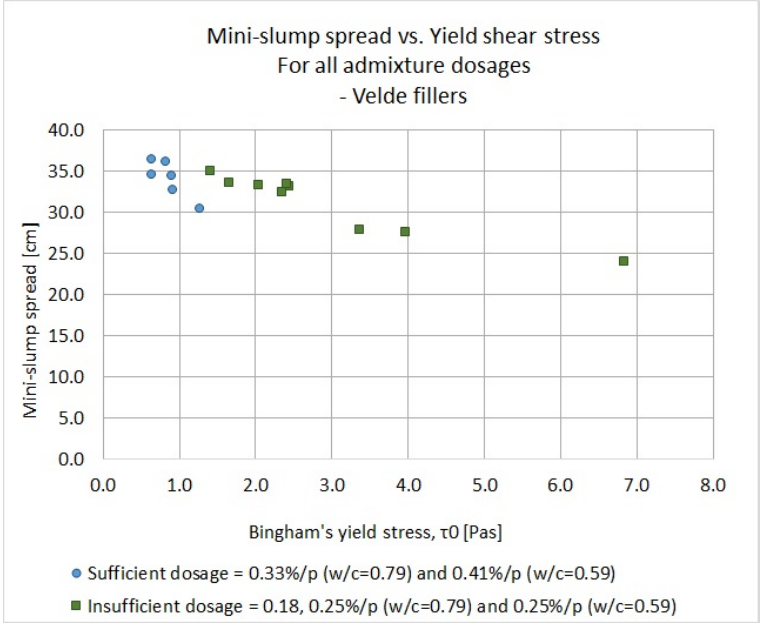


Figure 5.19: How the mini-slump spread and yield shear stress relationship behave when all the admixture dosages are included: 0.18, 0.25, 0.33%/powder (w/c=0.79) and 0.33, 0.41%/powder (w/c=0.59)

As clearly displayed in the previous section, the relationship between the mini-slump spread and plastic viscosity, μ, are perfectly related. It is odd that one parameter (mini-slump spread) could have a direct relationship with two individual properties (τ_0 and μ).

When the mini-slump spread has a unambiguous relationship with the plastic viscosity, it is hard to believe that it can replace the way of measuring the yield shear stress through the slump value. The mini-slump spread was an appropriate alternative way of determining the yield shear stress. But for future measurements, perhaps stick to the mini-slump value, or find an alternative way to determine the yield shear stress in a easier and more direct way.

5.4 The Effect of the Admixture Dosage and the Specific Surface Area (SSA) on the Rheology of the Matrix

5.4.1 The Effect of the Sufficient Admixture Dosages on the Flow Resistance

The results in Figure 5.20 look as if they have the same tendencies as the results in Figure 3.6 from [1]. The results line up close to the tendency line. What the graphs show, is when increasing the total specific surface area (SSA), namely the filler content, thus the particle concentration, the flow resistance also increases. The unambiguous relationship found in [1, 2], are backed up by these graphs. More for the w/c=0.59 than the w/c=0.79. If only results from Figure 5.20 were used, the unambiguous relationship could be confirmed, with no disturbance from the yield shear stress, τ_0. However, as the results have shown in this study, the clean-cut clarification cannot be done. But the relationship is still probably dominated by the SSA, given that the admixture dosage is sufficient to neglect the yield shear stress, τ_0.

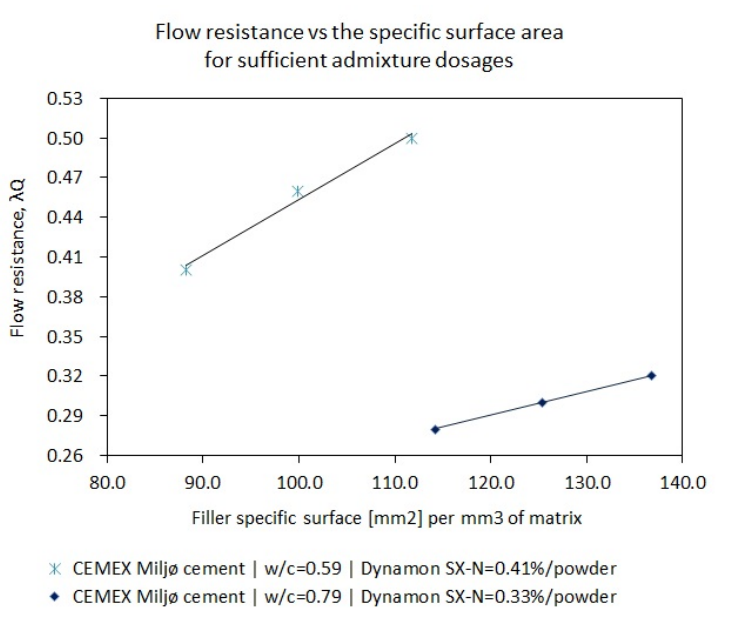


Figure 5.20: The results of the flow resistance and specific surface area relationship for the sufficient admixture dosages 0.33%/powder (w/c=0.79) and 0.41%/powder (w/c=0.59).

5.4.2 The Effect of the Sufficient Admixture Dosages on the Plastic Viscosity

As previously stated, the relationship between the flow resistance, λ_q, and the plastic viscosity, μ, are more or less unambiguous towards each other. With that knowledge in mind, the fact that the tendencies of the plastic viscosity and specific surface area (SSA) in Figure 5.21, are similar to the flow resistance and SSA in Figure 5.20, is not surprising. This would indicate a similar unambiguous relationship between the plastic viscosity and the SSA, as for the flow resistance and SSA.

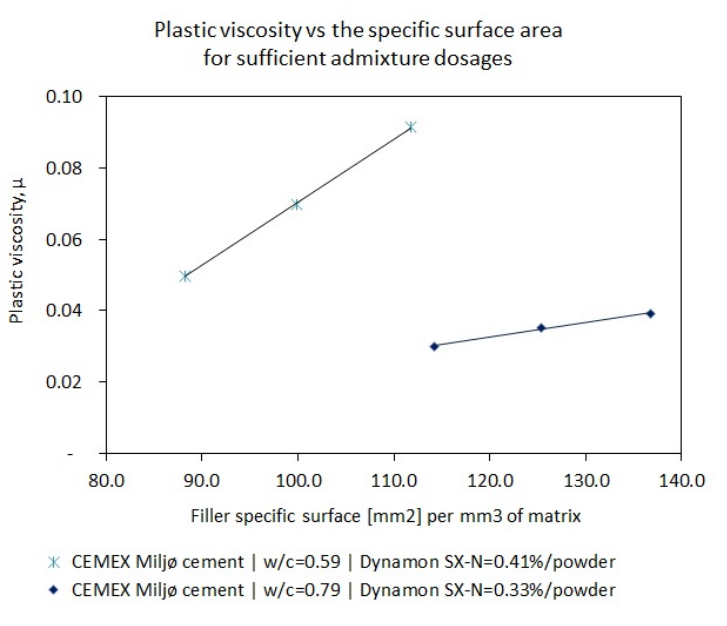


Figure 5.21: The results of the plastic viscosity and specific surface area relationship for the sufficient admixture dosages 0.33%/powder (w/c=0.79) and 0.41%/powder (w/c=0.59).

5.4.3 The Effect of the Insufficient Admixture Dosages on the Yield Shear Stress

The yield shear stress, τ_0, and the specific surface area (SSA) relationship for the insufficient admixture dosages in the results, is displayed in Figure 5.22.

It has previously been stated that the yield shear stresses for the insufficient admixture dosages are too high to use the flow property results actively. This is obvious in Figure 5.22. For both the w/c=0.79-series of results, the yield shear stress does not seem to increase in any significant way, when the SSA increases. The results are on the tendency line, which can mean that the admixture dosage is too low, but at least it is consistent.

For the w/c=0.59-case, it seems as if the yield shear stresses increase, with increasing SSA. But as the results increase in the same direction, they are still somewhat scattered. This could be due to the higher particle concentration, than the w/c=0.79. But the exact reason is unclear. Performing more measurements could clarify this.

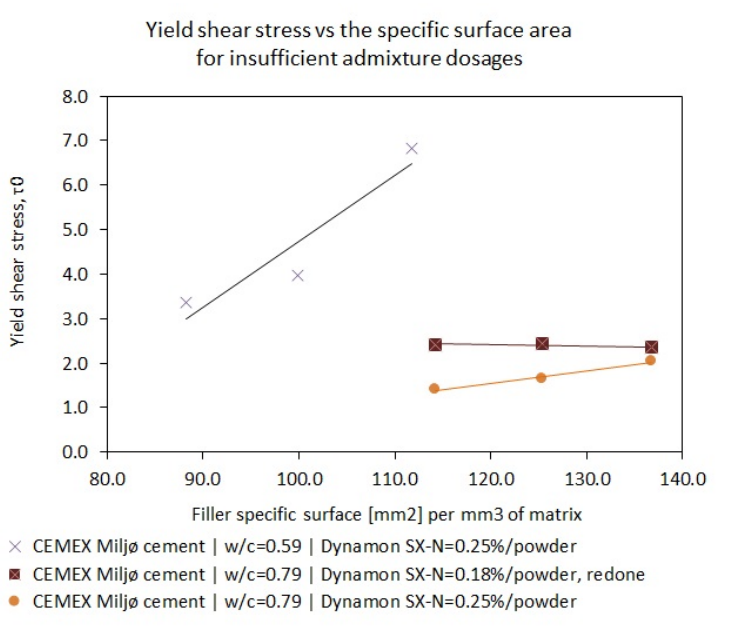


Figure 5.22: The results of the yield shear stress and specific surface area relationship for the insufficient admixture dosages 0.18, 0.25%/powder (w/c=0.79) and 0.33%/powder (w/c=0.59).

5.5 The Effect of Parameter Variation on New and Previous Results, with Regards to the Specific Surface Area (SSA)

5.5.1 The Effect of Parameter Variation on the w/c=0.59, only New Results

As mentioned in Section 3.5, the results from this study cannot be compared in the same graph as Figure 3.6, due to the different methods determining the particle size distribution (PSD), thus the SSA. This implies the results for the w/c=0.59 are displayed in their own graph, Figure 5.23.

The figure shows the results lining up almost perfect, with a slight difference in the middle results for both the admixture dosages, but more for the lowest dosage. This difference will probably reduce to nothing, with an additional increase of admixture dosage.

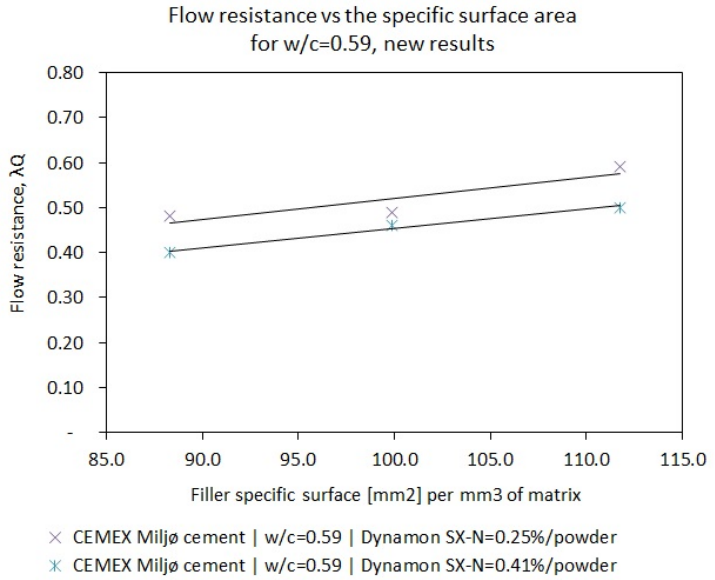


Figure 5.23: How the flow resistances from [3] are affected when increasing the admixture dosage. For w/c=0.59.

5.5.2 The Effect of Parameter Variation on the w/c=0.79, Previous and New Results

In Figure 5.24 the results from [3] are displayed with the admixture dosage of '0.18%/powder, previous'. The results are quite scattered, and do not form a linear relationship as first assumed. For this study, this matrix-mix was redone to indicate the same tendencies as in [3], noted as '0.18%/powder, redone'. The same kind of tendencies are shown, but to a larger extent with higher flow resistances, λ_q, in the matrix. The redone results together with the results with increase admixture dosages, are shifted to the right for the [3]'s results due to the higher SSA for the intermediate filler used in 2016 (this study), than the one used in 2015 ([3]). See the SSAs in Table 5.1.

Even the results with 0.25%/powder, increased dosage from [3], are still scattered and probably also influenced by the matrix's yield shear stress, τ_0. That admixture increase was apparently insufficient to remove the disturbances. Looking at the graphs, when increasing the admixture dosage yet another time, up to 0.33%/powder, this seems to be the minimum sufficient admixture dosage for these results. This dosage is finally sufficient enough to remove disturbances from the yield shear stress, and to make the flow resistances behave in a linear matter.

Why are the variation in flow resistances largest in the middle results of SSA for all three of the insufficient admixture dosages? The lowest SSAs vary to some extent when the admixture dosage varies, while for the highest SSAs, barely any variation is made. This is very peculiar, but the reason is uncertain.

The results in Figure 5.24 obviously confirm that the flow resistance is unambiguously related to the specific surface area (SSA), given that a sufficient admixture dosage is added to the matrix.

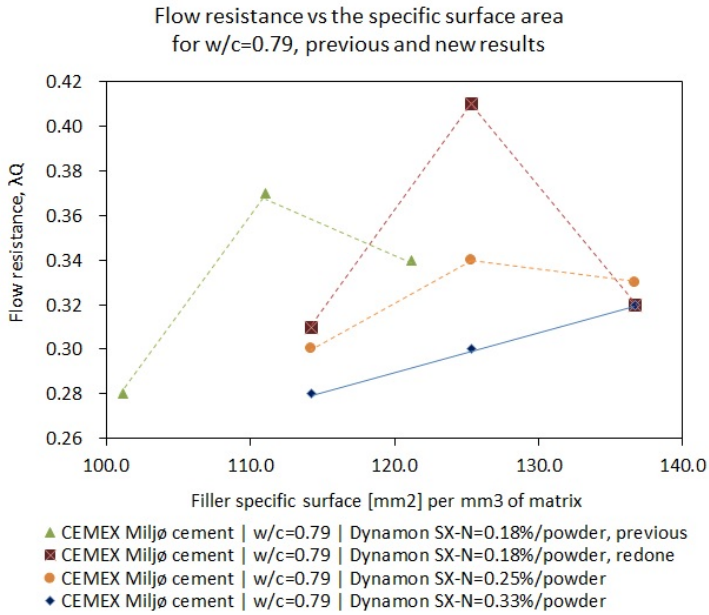


Figure 5.24: How the flow resistances from [3] are affected when increasing the admixture dosage. For previous and new w/c=0.79-results.

5.6 The Separate Study Regarding the Feiring Bruk Fillers

Measurements have been performed with Feiring Bruk's two fillers as the intermediate filler in the matrices. Through these measurements, the effect of fillers produced by different crushing methods was measured with respect to SSA. The fillers in question were the two fillers from Feiring Bruk, and the intermediate filler from Velde worked as the reference filler for the measurements. Velde's crushing method consists of several crushing stages, with a final crushing stage which include a vertical shaft impactor (VSI) and a wind sieve. The two fillers from Feiring Bruk are taken out after the first crushing stage (primary subbus) and the second crushing stage (0/2-filler) (Chapter 2).

5.6.1 The Particle Grading

Figure 5.25, which has the particle size range of 0.1-63 μm, shows similar grading for all three fillers after the SediGraph analysis. Feiring Bruk's primary subbus shows a slightly higher content of fine particles followed by Velde's intermediate and then Feiring Bruk's 0/2-filler. Solely the SediGraph analysis is too little information to determine anything. A combination of the mechanical sieving and the SediGraph results must be presented. See Figure 5.26.

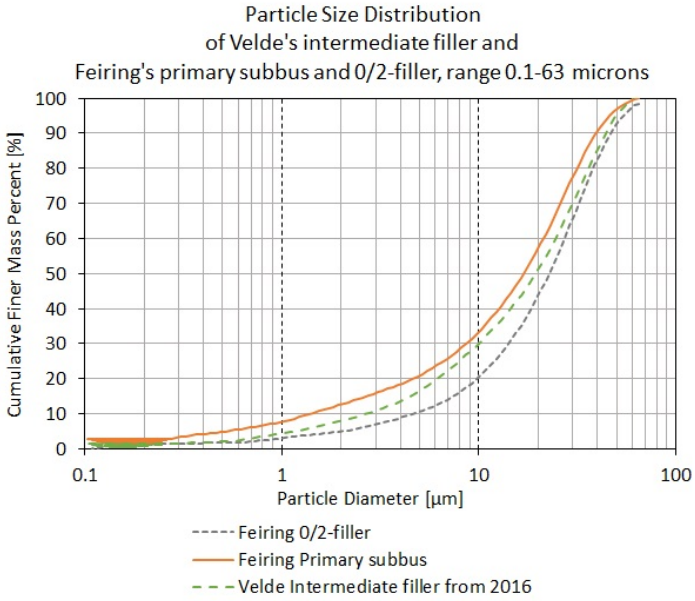


Figure 5.25: The SediGraph results of the intermediate filler from Velde and the two fillers from Feiring Bruk (Feiring). Range 0.1-63 μm.

In Figure 5.26 Velde's intermediate filler contains a higher amount of particles $\leq$63 μm than the Feiring Bruk ones; this will give the highest specific surface area (SSA) of the three. After the Velde, in SSA terms, follows the primary subbus and then the 0/2-filler. The higher the SSA, the higher the flow resistance, λ_q. As mentioned in the discussion regarding Figure 5.25, on which of the fillers contained the most fine particles when combining the mechanical sieving and the SediGraph results, the presumed primary subbus was in fact the second finest. This clearly states the importance of the combination.

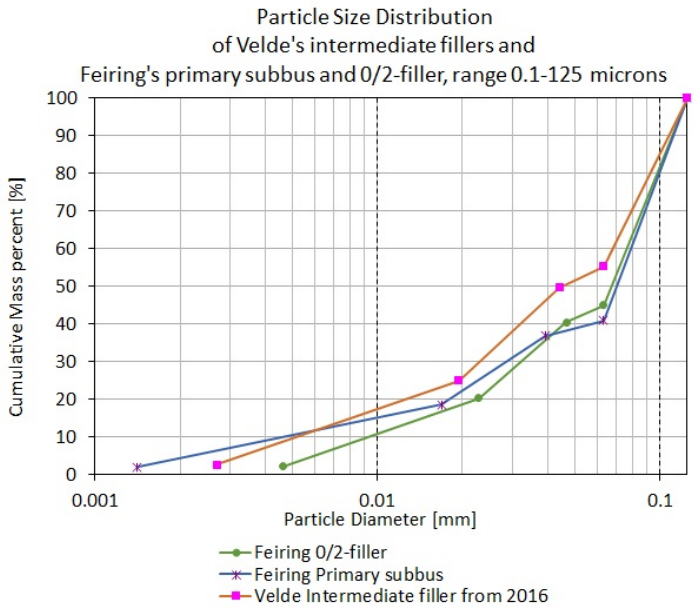


Figure 5.26: The mechanical sieving and SediGraph Analysis. The differences between the intermediate filler from Velde and the two fillers from Feiring Bruk (Feiring). Range 0.1-125 μm.

5.6.2 The Specific Surface Area (SSA)

Section 3.1.2 explains how the specific surface area (SSA) has been calculated through the data retrieved from the particle size distribution (PSD). According to the PSDs of the three, displayed in Figure 5.26, Velde's intermediate filler ranked finest, followed by Feiring Bruk's primary subbus as the second finest, and Feiring Bruk's 0/2-filler as the least fine. As Velde's intermediate works primarily as a reference filler, which means comparison with its SSA will not be discussed.

Due to the different crushing methods used for Feiring Bruk's fillers, direct comparison with regards to property similarities is difficult. The comparison will be roughly how they are ranked to each other based on how well they correlate with regards to the Bingham relationship, Figure 3.3, and the relationship between the flow resistances, λ_q, and the SSA.

Table 5.3: Calculated specific surface areas of the intermediate filler from Velde used in 2016 (this study), and the two fillers from Feiring Bruk.

	Fillers	**Specific Surface area [1/mm]**
Velde	**Intermediate (2016)**	357
Feiring Bruk	**Primary subbus**	300
	0/2 mm	243

5.7 The Bingham Relationship on the Feiring Bruk Fillers

The Figure 5.27 shows the behavior between the yield shear stress, τ_0, and the plastic viscosity, μ, for the Velde and Feiring Bruk fillers. All the matrices were mixed with an admixture dosage of 0.41%/powder. Compared to Figure 5.15, this is a sufficient dosage with regards to the Velde filler in the matrices, and apparently for the 0/2-filler. As viewed in Figure 5.27, the chosen admixture dosage is clearly insufficient with regards to the primary subbus. This is probably due to its higher specific surface area (SSA). This means that the flow resistance due to the primary subbus, will be disturbed by a too high yield shear stress.

Comparing the Figure 5.27 results with the Bingham relationship in Figure 3.3, it is clear that the 0/2-filler's yield shear stresses in these results are low enough to be neglected. This indicates that the 0/2-filler matrices with this chosen dosage behave as a Bingham fluid, closely related to the plastic viscosity with a negligible yield shear stress. And for the primary subbus to behave as a Bingham fluid, additional admixture needs to be added.

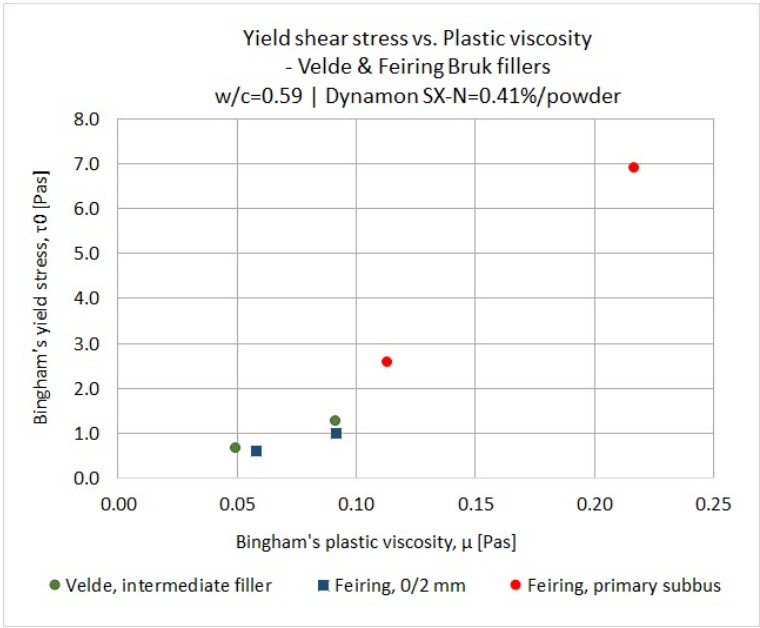


Figure 5.27: How the yield shear stress and plastic viscosity relationship behave when the admixture dosages is 0.41%/powder, w/c=0.59 and the intermediate fillers for the different results, are from Velde and Feiring Bruk (Feiring).

5.8 The Effect of the Feiring Bruk Fillers on the Flow Resistance

Figure 5.28 shows the flow resistances, λ_q, related to the Feiring Bruk's fillers. The primary subbus gives higher flow resistances than the 0/2-filler. This is due to it having a higher SSA than the 0/2-filler (see Table 5.3).

Between the two, the primary subbus results in a lower quality filler than the 0/2-filler. This is due to the primary subbus' higher flow resistances related to the SSA. This means that the crushing method used for the 0/2-filler has a beneficial effect on the matrix's flow properties when it comes to the rheology.

It even looks as though both of the filler's effect on the flow resistance can be unambiguously related to the SSA.

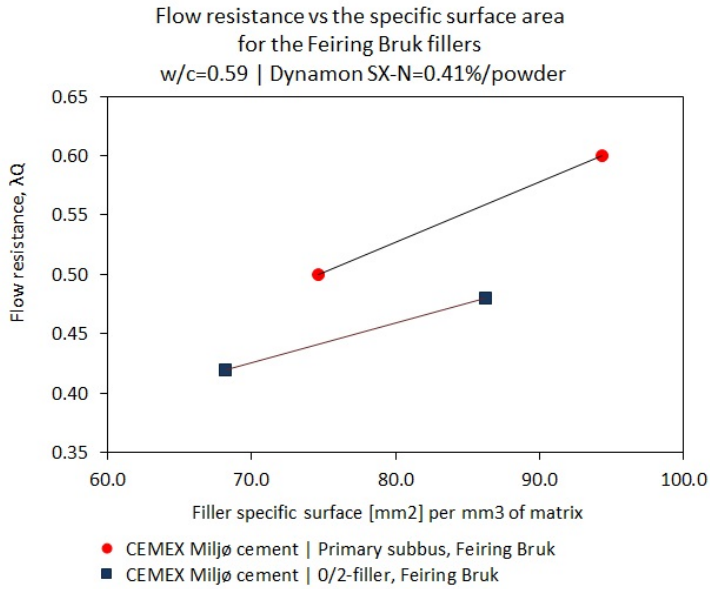


Figure 5.28: How the different fillers from Velde and Feiring Bruk affect the flow resistance when the admixture dosages is 0.41%/powder and w/c=0.59.

5.9 Possible Errors

Rheometer

One possible error could be found in the rheometer results. The machine was programmed to have a constant temperature of 20 °C at all times during the measurements, but this was not always checked consecutively.The measurements done as the first each new day at the laboratory, may or may not have been run with a lower temperature than 20 °C. This was discovered during one of the last measurements, when the temperature was randomly checked and it showed 10 °C. Be sure to check this every time.

Particle Size Distribution / Sieving

The PSD of the intermediate filler used in these measurements turned out to be more fine than the one this fall. One possible explanation could be that, as mentioned in Section 4.1.1, the intermediate filler was dried completely, and the one used this fall was not. A possible difference in the PSD could be that by completely drying the sand, all the smallest fine particles were able to join the intermediate filler-mix, while the sand mixture from Velde this fall was not dried. And there is a possibility that because of some moisture in the sand mixture, the finest of particles stuck together, and would not be sieved through. Some of the finest particles tend to stick to the surface of larger particles, and thus will not be sieved either.

SediGraph

The SediGraph assumes spherical shape of the particles that run through it. The fillers from Feiring Bruk are not spherical, rather more angular. This could interfere with the results from the sedimentation measurements.

With respect to particle dispersion, insufficient dispersion would result in smaller particles adhering to the surface of the larger and/or to each other, thus artificially coarsening the PSD. This can be expected to be a problem only for particles smaller than about 0.001 mm. [2]

Calculation of the Matrix Recipes

For calculating the matrix recipes, a spreadsheet [15] was used. The measurements were to be the same as the ones used in [1]. When calculating the component amounts for the recipe, the densities of the different components are needed. For all the recipes, done in [3] and for this study, densities already predefined in the spreadsheet, were used. What was figured out after the measurements were finished, was that the actual densities were not exactly the same as the ones in the spreadsheet. The percentages of error are presented in Figure 5.4. This, of course, affects the results in some way, but to what extent is unknown. Since this mistake was done for both this study and in [3], then the results will be comparable.

Table 5.4: Errors between used and actual cement and filler densities.

	Used density [kg/dm^3]	**Actual density [kg/dm^3]**	**Percentage difference**
CEMEX	3.15	3.06	+ 2.9 %
Velde fillers	2.7	2.64	+ 2.3 %
Feiring Bruk fillers	2.7	2.84	- 5.0 %
'+' = used density >actual density '-' = used density <actual density			

Chapter 6
Conclusion

6.1 Conclusion

The rheological parameters yield shear stress, τ_0, and plastic viscosity, μ are generally more sensitive for variations in the matrix's composition, than the results from the empirical methods; FlowCyl and mini-slump spread.

For the rheological relationships, when the admixture dosage was sufficient, the yield shear stress was low enough to be neglected, and the matrix's behavior could be related to the plastic viscosity. This indicated also the matrix's flow resistance to be perfectly related to the plastic viscosity. However, when the results included both the sufficient and the insufficient admixture dosages, the theoretical behavior was disturbed.

Because the flow resistance and the plastic viscosity are perfectly related to each other, when the admixture dosage is sufficient, implies that these two's behavior toward the specific surface area (SSA) are similar. Both the rheological parameters to the SSA seem to have an unambiguous relationship.

Since the mini-slump spread was the common method to determine the plastic viscosity, there is no surprise that their relationship correlated perfectly despite including both the sufficient and the insufficient admixture dosages.

Finally, what the results show, given a sufficient admixture dosage, reduces the yield shear stress to a negligible level. This indicates the filler's effect on the matrix's flow resistance, and thus indirectly the plastic viscosity, to be unambiguous and predictable with respect to SSA. This gives a one-parameter way of characterizing the matrix's flow properties, when keeping in mind the admixture dosage.

What does this mean in the bigger picture? It can mean, for Velde, that they can in a larger specter focus on the SSA when they put together their concrete recipes. How the SSA directly affects the properties of the matrix, and how those properties again affect the concrete. They can then use the SSA as a control parameter in their production.

Conclusion With Regards to the Feiring Bruk Fillers

Between the two, the primary subbus results in a lower quality filler than the 0/2-filler. This is due to the higher flow resistances related to the SSA, that the matrices produce. This means that the crushing method used for the 0/2-filler has a beneficial effect on the matrix's flow properties when it comes to the rheology, for these measurements.

It even seems that both of the fillers' effect on the flow resistance is unambiguously related to the SSA.

6.2 Possible Future Studies

6.2.1 Computational Simulation of the Matrix's Behavior

Jon Spangenberg (assistent professor at The Technical Universtiy of Denmark (DTU)) is currently theoretically testing the effect of the matrix's yield shear stress, τ_0. While this study experimentally is testing the same effect. Spangenberg plans on testing this with a computational fluid dynamic model that simulates the matrix's yield shear stress' effect on the basis of previous results from FlowCyl-measurements performed by Rolands Cepuritis (post.doc at the department of Concrete Technology at NTNU).

The computational model is generated by a set of results from Cepuritis' dissertation [2]. Spangenberg compares the yield shear stress and the plastic viscosity, μ, and sets up the corresponding flow resistances, λ_q, of the different results. If he accomplishes the good correlation between the measured and the computed flow resistance, then the model is acceptable to establish the effect of the yield shear stress.

The correlation can help isolate specific parameters, to see how this affects the flow resistance. This isolation was not possible to performed for this study, it will be interesting to see how this model turns out.

The work Spangenberg does, is part of the work group (WG) 3 in the Mikroproporsjonering i Knust Sand (Micro proportioning with crushed sand) (MiKS)-project. This work will be exiting to follow up, and see if his results match the results from this study.

6.2.2 Continuation of These Measurements

To get a clearer picture of the behaviors of how the different parameters affect the matrix's flow properties, a new study should be performed with broader variations in the measured parameters. This has already started in the research project for MiKS, as mentioned above.

6.2.3 Possible Assessments With Regards to the Admixture Dosage

A Possible Determination of an Admixture Dosage Threshold Level

Through the results gained by this study, it seems that there is a kind of threshold level that the admixture dosage needs to reach, in order for the results not to be disturbed by the yield shear stress, τ_0, as mentioned in Section 5.2.2 and Section 5.3.1.

What this threshold level is, depends on several parameters; the water/cement-ratio (w/c), the water/powder-ratio (w/p), the filler content (fi/c) and etc. The possibility of obtaining this threshold level is unsure, however, perhaps it can be determined through the computational fluid dynamic model mentioned in Section 6.2.1.

An Alternative Way to Determine the Admixture Dosage

For these measurements the admixture dosage was determined as a percentage of the total amount of powder. While in [1, 3], the admixture dosage was determined as a percentage of total amount of cement.

When the filler content exceeds a certain amount (a guess: say around fi/c=0.50), the total (cement+filler) (powder) content can result in an amount significantly higher than the cement content. The amount of particles affect how well the admixture dosage works. By determining the admixture dosage solely by the cement content, gives the perception of the reality a mistaken image.

For future studies with large amounts of fillers, with the determination of the admixture dosage as a percentage of the total cement content, be sure to be clear about the choice, and specify the filler content.

References

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Appendix A

CEMEX Environmental Cement

Data sheet about the CEMEX Environmental cement used in the measurements. See the next page (1).

MILJØSEMENT
CEM II/B-S 52,5 N

Tekniske data

April 2015

Tilfredsstiller kravene ihht. EN 197-1: CEM II/B-S 52,5 N
Produktet er sertifisert (CE-merket) ihht. EN 197-1 av VDZ, Tyskland.

Egenskaper

Tilsetning
MILJØSEMENT kan brukes med tilsetningsstoffer, luftinnføringsmidler, silika, flygeaske og slagg. Prøveblandinger bør alltid foretas for å sikre riktig dosering.

Forsiktighetsregler ved bruk av sement
Tørt sementpulver har ingen skadelig effekt på tørr hud. Fuktig sement virker aggressiv på hud, og på slimhinner i øyne, nese og svelg.

- Bruk derfor hansker, støvmaske og vernebriller hvor det er fare for sprut.
- Sement på hud vaskes bort med såpe og rikelig rent vann. Sørg for grundig vask etter arbeidstidens slutt. Hvis det oppstår hud irritasjon, kontakt lege.

Har man fått sement i øynene:
- Skyll snarest med rikelig med vann.
- Ikke gni!
- Kontakt lege.

Har man fått sement i nese, svelg eller mage:
- Drikk rikelige mengder med rent vann.
- Kontakt lege.

Typiske data:

Kjemiske egenskaper		vekt %
Kalk	(CaO)	56
Silisium	(SiO_2)	25
Aluminium	(Al_2O_3)	6,3
Jern	(Fe_2O_3)	2,1
Magnesium	(MgO)	4,0
Sulfat	(SO_3)	3,1
Kalium	(K_2O)	0,82
Natrium	(Na_2O)	0,31
Alkali ekv.	(Na_2Oekv)	0,80
(C_3A)		5,3
Glødetap		1,7
Uløselig rest		0,6
Vannnløslig klorid	(Cl^-)	0,07
Vannnløslig krom	$Cr^{(VI)}$	<2 mg/kg

Fysiske data		
Finhet (blaine)		460 m^2/kg
Densitet		3,06 g/cm^3
Bulkdensitet		1,1g/cm^3
Andel slagg		Ca 33%
Bindetid		170 min
Ekspansjon		1,0 mm
Trykkfasthet	1 d	16 MPa
	2 d	28 MPa
	28 d	59 MPa

CE
0840

CEMEX OstZement GmbH
Frankfurter Chaussee
15562 Rüdersdorf
Werk Rüdersdorf

0840-CPD-5510-221200-05
EN 197-1
CEM II/B-S 52,5 N

CEMEX AS
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Grønland 70A
N-3045 DRAMMEN

Appendix B

Mapei, Dynamon SX-N, Superplasticizing Admixture

Data sheet about the superplasticizing admixture used in the measurements. See the next pages (3).

MAPEI

Dynamon SX-N

CE
EN 934-2
T 3.1/3.2

Superplasticising admixture

PRODUCT DESCRIPTION
Dynamon SX-N is a very efficient liquid superplasticising admixture, based on modified acrylic polymers.
The product belongs to the **Dynamon System** based on the DPP (Design Performance Polymers) technology, a new chemical process that can model the admixture's properties in relation to specific performances required for concrete. The process is developed by means of a complete design and production of monomers (an exclusive Mapei know-how).

AREAS OF APPLICATION
Dynamon SX-N is an all-round product to be used in nearly all types of concrete to improve the workability and/or reduce the amount of water needed.

Some specific applications are:

- Concrete with reduced permeability with specifications as to very high mechanical strength and to long durability in aggressive environments.
- Concrete with high levels of workability (consistency classes S4 or S5 - according to EN 206)
- Self-compacting concrete where high slump retention is required. If extra stabilisation is needed, a viscosity enhancing agent, **Viscofluid** or **Viscostar** can be used.
- Production of frost resistant concrete - in combination with air entraining agents (AEA), **Mapeair**. The correct type and amount of AEA is dependent on the properties of the other available ingredients.
- Concrete for flooring where a smooth concrete with high workability is aimed for. Larger dosages and lower tempe ratures may increase the retardation.

TECHNICAL PROPERTIES
Dynamon SX-N is an aqueous solution of active acrylic polymers that very efficiently disperses clusters of cement grains.

This effect can in principle be used in the following three ways:

1. To reduce the amount of added water, yet retain the same workability. Lower water to cement ratio means higher mechanical strength, reduced permeability and increased durability.
2. To increase workability compared to concrete with equal water to cement ratio. With the same mechanical strength the casting is facilitated.
3. To reduce both the amount of water and the amount of cement without changing the concrete's mechanical strength. In this way it is possible to

Dynamon SX-N

reduce the total cost of the concrete (less cement), reduce the concrete's shrinkage potential for (less water) and reduce the possibility of cracks due to temperature gradients (less hydration heat). Especially with concretes that normally have high amounts of cement, this effect is very important.

COMPATIBILITY WITH OTHER PRODUCTS

Dynamon SX-N can be combined with other admixtures from Mapei; such as a set-accelerating admixture, **Mapefast** or a set-retarding admixture, **Mapetard**. The product is also compatible with air entraining admixtures to produce frost resistant concrete, **Mapeair**.

The choice of admixture is done after an evaluation of the properties of the other ingredients in the mix.

DOSAGE

To obtain the prescribed properties (i.e. strength, durability, workability, cement reduction), **Dynamon SX-N** is added in dosages between 0.4 and 2.0% of the amount of cement + fly ash + microsilica. Increased dosages will also increase the slump retention, i.e. the time to be able to work with the concrete.

Higher dosages and lower temperatures will delay the setting of the concrete. To obtain correct knowledge, tests with actual parameters are advisable, especially before larger pours.

As opposed to traditional superplasticisers based on melamines or naphtalenes, the maximum effect of **Dynamon SX-N** is obtained regardless of when it isaddes during the mixing procedure it is added, but the time of addition can influence the mixing time. If at least 80 % of the mixing water is added before **Dynamon SX-N** the required mixing time will generally be shortest. It is nevertheless important to perform using the actual mixing equipment.

Dynamon SX-N can also be added directly into the truck on site. The concrete should then be mixed at full speed at least for one minute pr m^3 of concrete, and never shorter than 5 minutes.

PACKAGING

Dynamon SX-N is available in 25 liter cans, 200 liter drums, 1000 liter IBC tanks and in tank.

STORAGE

The product must be stored at temperatures between +8 and +35°C, and will retain its properties for at least one year if stored unopened in its original packaging. If the product is exposed to direct sunlight, colour variation may occur, but this will not affect the technical properties of the product.

SAFETY INSTRUCTIONS FOR PREPARATION AND USE

Dynamon SX-N is not considered dangerous according to European regulations regarding classification of chemicals. It is recommended to wear gloves and goggles and to take usual precautions for handling of chemicals.

For further and complete information about safe use of our product, please refer to our latest version of the Safety Data Sheet.

PRODUCT FOR PROFESSIONAL USE

WARNING

Although the technical details and recommendations contained in this product data sheet correspond to the best of our knowledge and experience, all the above - information must, in every case, be taken as merely indicative and subject to confirmation after long-term practical application: for this reason, anyone who intends to use the product must ensure beforehand that it is suitable for the envisaged application: in every case, the user alone is fully responsible for any consequences deriving from the use of the product.

Please refer to the current version of the technical data sheet, available from our web site www.mapei.no

All relevant references for the product are available upon request and from www.mapei.no

Dynamon SX-N

TECHNICAL DATA (typical values)

PRODUCT IDENTITY	
Appearance:	liquid
Colour:	yellowish brown
Viscosity:	easy flowing; < 30 mPa·s
Solids content (%:)	18.5 ± 1.0
Density (g/cm³):	1.06 ± 0.02
pH:	6.5 ± 1
Chloride content (%):	< 0.05
Alkali content (Na_2O-equivalents) (%):	< 2.0

10.03.2015 GB

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Appendix C
The Project Parameters

See the next page (1).

Table C.1: The project parameters used in the measurements in this study. CEMEX Environmental cement is used for all. SP=Super plasticizer, admixture type, p=powder. FB=Feiring Bruk. The combi.numbers without values are from previous studies.

Parameter	Combi. number	w/c	SP type	SP/p	Fine	Interm.	Coarse	fi/c
Ref. filler grading	**4**	0.59	SX-N	0.33%	10%	50%	40%	0.51
	5	0.59	SX-N	0.25%	10%	50%	40%	0.51
	6	0.59	SX-N	0.41%	10%	50%	40%	0.51
	7	0.79	SX-N	0.18%	10%	50%	40%	0.7
	8	0.79	SX-N	0.25%	10%	50%	40%	0.7
	9	0.79	SX-N	0.33%	10%	50%	40%	0.7
fi/c reduced	**13**	0.59	SX-N	0.33%	10%	50%	40%	0.46
	14	0.59	SX-N	0.25%	10%	50%	40%	0.46
	15	0.59	SX-N	0.41%	10%	50%	40%	0.46
	16	0.79	SX-N	0.18%	10%	50%	40%	0.65
	17	0.79	SX-N	0.25%	10%	50%	40%	0.65
	18	0.79	SX-N	0.33%	10%	50%	40%	0.65
fi/c increased	**22**	0.59	SX-N	0.33%	10%	50%	40%	0.56
	23	0.59	SX-N	0.25%	10%	50%	40%	0.56
	24	0.59	SX-N	0.41%	10%	50%	40%	0.56
	25	0.79	SX-N	0.18%	10%	50%	40%	0.75
	26	0.79	SX-N	0.25%	10%	50%	40%	0.75
	27	0.79	SX-N	0.33%	10%	50%	40%	0.75
FB prisub	28	0.59	SX-N	0.41%	10%	50%	40%	0.46
FB 0/2	29	0.59	SX-N	0.41%	10%	50%	40%	0.46
From 2015	30	0.79	SX-N	0.18%	10%	50%	40%	0.70
	31	0.79	SX-N	0.18%	10%	50%	40%	0.65
	32	0.79	SX-N	0.18%	10%	50%	40%	0.75
FB prisub	33	0.59	SX-N	0.41%	10%	50%	40%	0.56
FB 0/2	34	0.59	SX-N	0.41%	10%	50%	40%	0.56

Appendix D

Particle Size Distribution and Frequency Curves for The Fillers

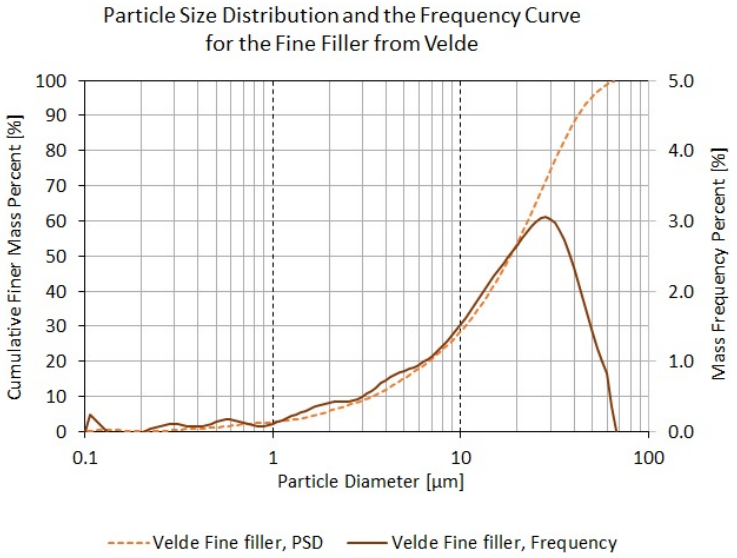

Figure D.1: Cumulative Finer Mass Percent and Mass Frequency Percent from the SediGraph Analysis, for the fine Velde filler.

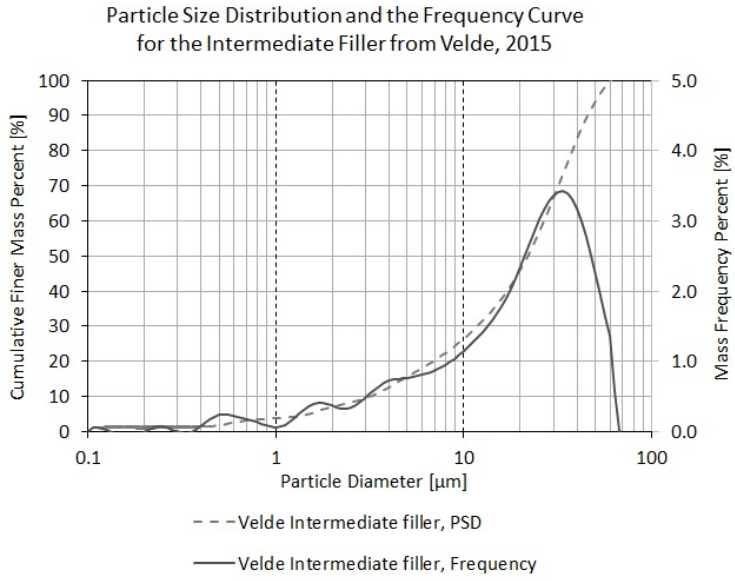

Figure D.2: Cumulative Finer Mass Percent and Mass Frequency Percent from the SediGraph Analysis, for the intermediate Velde filler, from 2015.

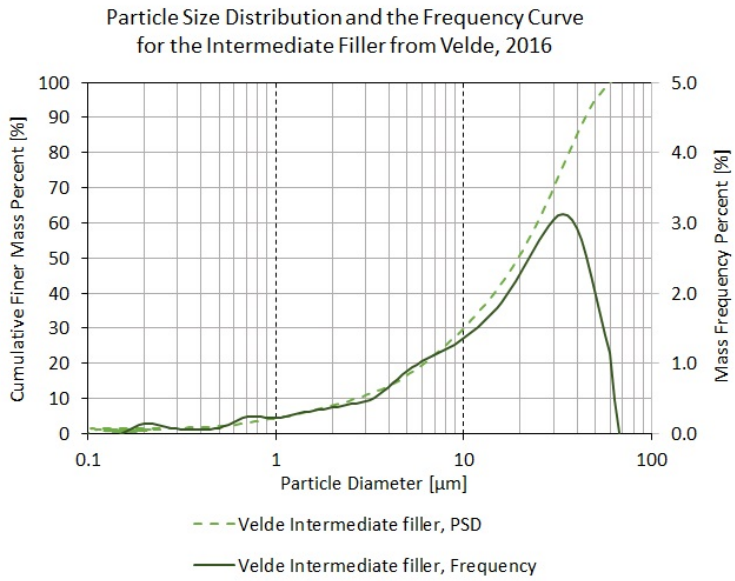

Figure D.3: Cumulative Finer Mass Percent and Mass Frequency Percent from the SediGraph Analysis, for the intermediate Velde filler, from 2016.

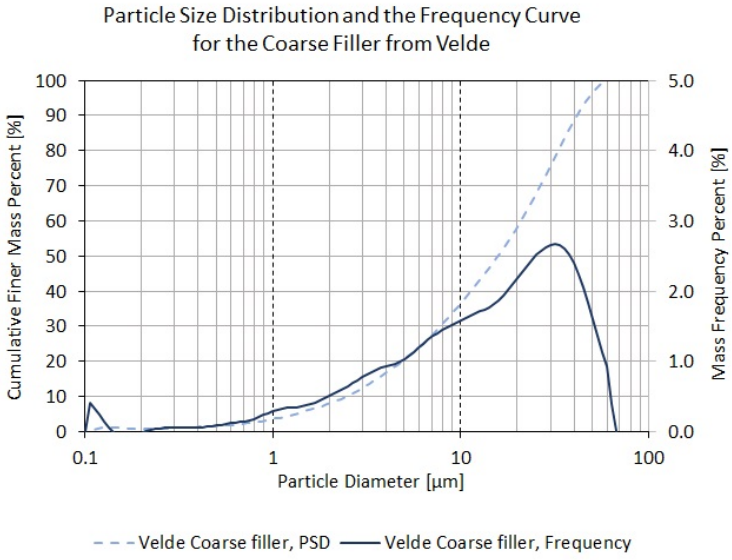

Figure D.4: Cumulative Finer Mass Percent and Mass Frequency Percent from the SediGraph Analysis, for the coarse Velde filler.

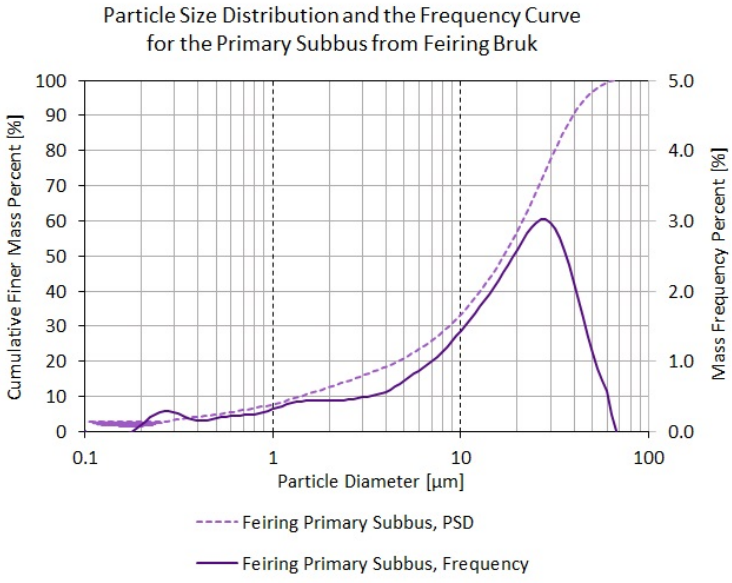

Figure D.5: Cumulative Finer Mass Percent and Mass Frequency Percent from the SediGraph Analysis, for the primary subbus Feiring Bruk filler.

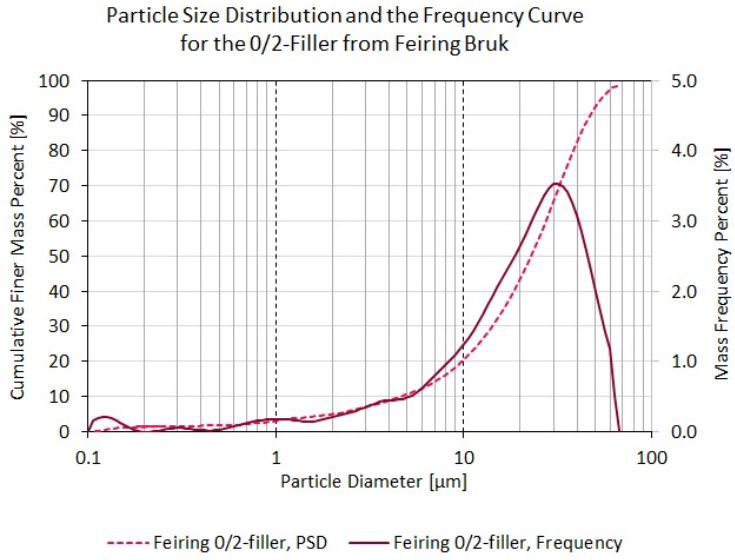

Figure D.6: Cumulative Finer Mass Percent and Mass Frequency Percent from the SediGraph Analysis, for the 0/2-filler from Feiring Bruk.

Appendix E
Rheological Results

See the next pages (2).

Table E.1: First part of all the results from the rheological measurements. SP=Super plasticizer, admixture type, p=powder. FB=Feiring Bruk. The combi.numbers without values are from previous studies.

Parameter	Combi. number	w/c	SP/p	fi/c	Flow resistance	FlowCyl delay?	Mini-slump [min.sec] Time after FlowCyl
Ref. filler grading	**4**	0.59	0.33 %	0.51	0.33		
	5	0.59	0.25 %	0.51	0.49	no	1.20
	6	0.59	0.41 %	0.51	0.46	30sec	0.55
	7	0.79	0.18 %	0.7	0.37		
	8	0.79	0.25 %	0.7	0.34	no	0.40
	9	0.79	0.33 %	0.7	0.3	5sec	0.55
fi/c reduced	**13**	0.59	0.33 %	0.46	0.31		
	14	0.59	0.25 %	0.46	0.48	no	1.45
	15	0.59	0.41 %	0.46	0.4	5sec	0.55
	16	0.79	0.18 %	0.65	0.28		
	17	0.79	0.25 %	0.65	0.3	no	0.55
	18	0.79	0.33 %	0.65	0.28	no	1.30
fi/c increased	**22**	0.59	0.33 %	0.56	0.36		
	23	0.59	0.25 %	0.56	0.59	no	1.20
	24	0.59	0.41 %	0.56	0.5	10sec	1.20
	25	0.79	0.18 %	0.75	0.34		
	26	0.79	0.25 %	0.75	0.33	8sec	0.57
	27	0.79	0.33 %	0.75	0.32	10sec	0.55
FB prisub	**28**	0.59	0.41 %	0.46	0.5	10sec	0.50
FB 0/2	**29**	0.59	0.41 %	0.46	0.42	no	0.35
From 2015	**30**	0.79	0.18 %	0.70	0.41	15sec	0.57
	31	0.79	0.18 %	0.65	0.31	no	0.54
	32	0.79	0.18 %	0.75	0.32	no	1.20
FB prisub	**33**	0.59	0.41 %	0.56	0.6	no	1.25
FB 0/2	**34**	0.59	0.41 %	0.56	0.48	no	0.30

Table E.2: Second part of all the results from the rheological measurements. SP=Super plasticizer, admixture type, p=powder. FB=Feiring Bruk. The combi.numbers without values are from previous studies.

Parameter	**Combi. number**	**Mini-slump [cm] Average diameter**	**Rheometer [min.sec] Time after FlowCyl**	**Plastic viscosity,** μ	**Yield shear stress** τ_0
Ref. filler grading	**4**				
	5	27.6	6.32	0.14	3.96
	6	32.7	6.38	0.07	0.92
	7				
	8	33.6	6.23	0.06	1.65
	9	36.2	6.05	0.04	0.82
fi/c reduced	**13**				
	14	27.9	7.34	0.13	3.37
	15	34.6	8.40	0.05	0.05
	16				
	17	35.0	6.07	0.04	1.41
	18	36.5	6.35	0.03	0.63
fi/c increased	**22**				
	23	24.0	6.20	0.26	6.83
	24	30.5	6.20	0.09	1.27
	25				
	26	33.3	6.08	0.06	2.05
	27	34.5	6.15	0.04	0.90
FB prisub	**28**	28.4	7.47	0.11	2.56
FB 0/2	**29**	34.3	7.57	0.06	0.59
From 2015	**30**	33.1	7.27	0.07	2.44
	31	33.5	8.16	0.06	2.41
	32	32.5	6.36	0.06	2.35
FB prisub	**33**	23.4	6.45	0.22	6.89
FB 0/2	**34**	32.0	11.10	0.09	0.98