Modelling Bingham Suspensional Flow
Influence of Viscosity and Particle Properties
Applicable to Cementitious Materials

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Abstract

Simulation of fresh concrete flow has spurred with the advent of Self-Compacting Concrete, SCC. The fresh concrete rheology must be compatible with the reinforced formwork geometry to ensure complete and reliable form filling with smooth concrete surfaces. Predicting flow behavior in the formwork and linking the required rheological parameters to flow tests performed on the site will ensure an optimization of the casting process.

In this thesis, numerical simulation of concrete flow and particle behaviour is investigated, using both discrete as well as a continuous approach. Good correspondence was achieved with a Bingham material model used to simulate concrete laboratory tests (e.g. slump flow).

As crushed rock will be used more frequently in the future to achieve a 'greener' concrete, the mechanisms behind particle shape influences were investigated.

It is known that aggregate properties such as size, shape and surface roughness as well as its grading curve affect fresh concrete properties. An increased share of non-spherical particles in concrete increases the level of yield stress, $\tau_0$, and plastic viscosity, $\mu_{pl}$. The yield stress level may be decreased by adding superplasticizers, however, the plastic viscosity may not. An explanation for the behaviour of particles is sought after experimentally, analytically and numerically. Bingham parameter plastic viscosity is experimentally linked to particle shape. It was found that large particles orient themselves aligning their major axis with the fluid flow, whereas small particles in the colloidal range may rotate between larger particles. The rotation of crushed, non-spherical fine particles as well as particles of a few microns that agglomerate leads to an increased viscosity of the fluid.

Generally, numerical simulation of large scale quantitative analyses are performed rather smoothly with the continuous approach. Smaller scale details and phenomena are better captured qualitatively with the discrete particle approach. As computer speed and capacity constantly evolves, simulation detail and sample volume will be allowed to increase.

A future merging of the homogeneous fluid model with the particle approach to form particles in the fluid will feature the flow of concrete as the physical suspension that it represents. One single ellipsoidal particle in fluid was studied as a first step.

Key words: Self-Compacting Concrete, SCC, Fresh concrete flow, Numerical simulation, Viscosity, Open channel flow
Sammanfattning

Man har studerat simulering av betongens flöde sedan självkompakterande betong, SKB, började användas. Numerisk simulering av SKBs flöde kan säkerställa kompatibilitet mellan betongens reologi och armeringens och formens utförande för att optimera gjutprocessen.

I föreliggande avhandling undersöks betongens flöde med diskreta och en kontinuumbaserad simuleringsmetod. God överensstämmerse mellan simulerad Bingham-modell och prövningsmetoder för SKB (t. ex. konsistens) har noterats.

I och med att betongproduktionen ställs om till en större mängd krossad ballast harmekanismen bakom partikelformens inverkan undersökts.

Det är känt att ballastens egenskaper som storlek, form, ytans beskaffenhet och även kornfördelningskurvan har betydelse för den färska betongens egenskaper. En ökad andel icke-sfäriska partiklar ökar även betongens flytgränsspänning, $\tau_0$, och dess plastiska viskositet, $\mu_{pl}$. Det är möjligt att sänka flytgränsspänningsen med hjälp av superplasticerare, dock är det inte alltid lika trivialt att sänka betongens viskositet.

En förklaring till partiklars inverkan och fenomenologi har sökts experimentellt, numeriskt och analytiskt. Den plastiska viskositeten kan länkas experimentellt till de mindre partiklarnas kornform. Man finner att de större partiklarna riktar in sig med långsaxeln och följer fluidens flöde. Mindre partiklar roterar och agglomererar eventuellt och rör sig mellan de större partiklarna i en riktning som inte följer fluidens flöde i stort, vilket ger upphov till den ökade viskositeten.

En övergripande analys av betongens flöde kan göras med den kontinumbaserade ansatsen för att upptäcka zoner där eventuellt blockering kan komma att utvecklas. En högupplöst detaljstudie kompletterar sedan analysen inom valda delar kring dessa zoner för att analysera partikelfenomenet kvalitativt med hjälp av en partikelmodell. När datorkapaciteten ökar kommer även större volymer med högre detaljriktedom att kunna simuleras.
En framtida modell simulerar med stor sannolikhet partiklar i flöde, där betongens egenskaper som suspension till fullo kan simuleras. Som ett första litet steg mot framtiden har en ellipsoid i vätska simulerats.
List of Publications

The following papers are included in the thesis:


V. Gram, A., Silfwerbrand, J., Lagerblad, Particle Motion in Fluid - Analytical and Numerical Study submitted to Applied Rheology

The planning, programming, analyzing and writing were mainly performed by the main author. The co-authors have guided the work and contributed to the papers with comments and revisions. Gram has performed all the laboratory work except the tests presented in Section 4.6 (Paper IV) and is responsible for the evaluation of all experimental data. The femLego simulation of a falling ellipsoidal particle shown in Paper I and Paper V is part of a joint project at the Royal Institute of Technology (KTH).
Other publications by the author on the same topic:


## Contents

Preface iii  

Abstract v  

Sammanfattning vii  

List of Publications ix  

1 Introduction 1  

1.1 Concrete and Simulation 1  

1.2 Aim and Scope 2  

1.3 Limitations 3  

1.4 Outline of the Thesis 3  

1.5 Research Contribution 4  

2 Theory 5  

2.1 Rheology 5  

2.1.1 Introduction 5  

2.1.2 The Bingham Model 5  

2.2 Rheology of Incompressible Fluid with Particles 7  

2.2.1 Selected Analytical Solutions of Flow 8  

2.3 Particle Packing and Concrete Workability 9  

2.3.1 Introduction 9  

2.3.2 Maximum Particle Packing 10  

2.3.3 Optimal Packing by Particle Distribution 14
6.2 Paper II ................................................................. 39
6.3 Paper III ................................................................. 40
6.4 Paper IV ................................................................. 41
6.5 Paper V ................................................................. 41

7 Discussion ............................................................... 43

8 Conclusions and Further Research .................................. 45

References .................................................................. 51

A Appended papers ....................................................... 53
Chapter 1

Introduction

1.1 Concrete and Simulation

Good durability, easy fabrication and a relatively low cost make concrete our by far most common building material. It consists of about 60% – 80% aggregates bound by cement paste and possibly other hydraulic or pozzolanic products, sometimes including filler material. The smallest particles of the concrete paste are in the range of micrometers or even nanometers. The largest particles, the aggregates, are on the scale of several centimeters. The wide range in particle size as well as the density of the particle system makes concrete modelling both challenging and interesting. The scale of observation determines the detail and focus of the material inhomogeneities. The scaling determines whether the material is seen as homogeneous or inhomogeneous.

Of special interest is the simulation of Self-Compacting Concrete, SCC, also called Self-Consolidated Concrete in North America. SCC is a family of different types of concrete, usually rich in filler content and easily flowing. Its flow characteristics define the SCC workability, filling out the formwork under the influence of gravity alone. Fresh SCC may be described as a particle suspension, meaning particles distributed in a liquid SCC is leading the way in achieving highly complicated structures with possible bends and small nooks in the formwork that are to be completely filled. Simulating the flow of SCC in different formwork geometries may present an important way to control a proper casting process and ensure matching rheological properties of the concrete.

Outside Japan, Örjan Petersson, at the time at the Swedish Cement and Concrete Research Institute (CBI), was first to simulate SCC flow for geometries other than slump flow, Petersson and Hakami (2001) and Petersson (2003). This project is a continuation of his pioneering work. Simulation of SCC flow had previously been conducted in Japan to study blocking mechanisms, dynamic segregation and rheological parameters, for SCC and also for shotcrete. Since the issue of blocking was to be studied thoroughly when designing an SCC mix, early simulation of SCC at CBI focused on blocking with a discrete numerical approach, the distinct element method, DEM. J-ring and L-box were simulated in order to study blocking and rheological parameters. Distinct elements naturally allow an inhomogeneous approach.
in the small scale. Later on in this project, as larger volumes were modelled, a continuous approach has been introduced with Computational Fluid Dynamics, CFD. It allows larger scale modelling in order to put emphasis on satisfactory form filling and surface finish. Ever since Örjan Petersson’s first work, simulation of fresh concrete flow is a growing field of research interest, Roussel and Gram (2014). A brief overview on previous work on simulation of concrete flow is given in Paper I. Since it was published, two pieces of work are worth mentioning, modelling of dynamic segregation of a wall casting by Spangenberg et al. (2012), and a Lattice-Boltzman approach to modelling fiber orientation in castings depending on flow directions by Svec (2014). This latter approach is a computer efficient way to capture both fluid and particles in one numerical model with a novel approach.

1.2 Aim and Scope

The objective of this thesis is to gain an increased understanding of the phenomenology of aggregate properties influencing fresh concrete rheology by studies using numerical simulation and modelling. In order to do so, a convincing model, numerical and/or analytical, is to be found. It is known that filler and aggregate properties such as size, shape and surface roughness as well as its grading curve affect fresh concrete properties, Esping (2007) and Geiker et al. (2002). An increased share of non-spherical particles in concrete increases the level of yield stress, $\tau_0$, and plastic viscosity, $\mu_{pl}$. The yield stress level may be decreased by adding superplasticizers, however, the plastic viscosity may not. An explanation for the behaviour of small and large particles is sought after experimentally, analytically and numerically. One hypothesis to explain the increased Bingham parameters has been a model of rotation and movement of particles, were ellipses are thought to need more space than spheres. For this reason, an increased amount of paste is assumed to be adequate in order to decrease especially the viscosity. The study of fluid viscosity in this thesis involves several steps. These steps can be formulated as research questions, RQ.

The following research questions have been identified for the project:

RQ 1: Is it possible to simulate concrete flow?

The first research question is fundamental and it is assumed that it is possible to create a material model to adequately simulate concrete flow as a Bingham material.

RQ 2: Is it possible to obtain a value for plastic viscosity other than in a viscometer?

The second research question aims at finding an easy method to verify rheological parameters of the simulated Bingham material on-site.

RQ 3: Is there a simple way to determine particle shape?

The third research question aims at evaluating methods for easy determination of particle shape, since non-spherical particles shape is assumed to increase the viscosity.

RQ 4: How do particles behave during fluid flow and in what way does this behaviour affect suspensional viscosity?

The final research question aims at the phenomenological study of particles during fluid flow and how their behaviour influences workability.

The long-term goal of this research project is to break new grounds for an increased
understanding of (non-spherical) particle influence on concrete workability.

1.3 Limitations

The concrete considered here for modelling is regarded as a Bingham material that does not segregate. The Distinct Element Method (DEM) was used initially to model concrete including its ability to form granular arches/bridges and block behind rebars. Only small volumes are modeled with this approach, since it is a time consuming modelling method requiring significant computational power. The homogeneous approach using Computational Fluid Dynamics (CFD) is a simplified model, since aggregates of the mix are disregarded on a small scale. The modelling of a connection between mix design and the rheology of concrete was not done in this project. As far as simulation of SCC test methods goes, they have been limited to the L-box, J-ring and slump flow. Previously, a continuous CFD material model in the macroscale was calibrated, Gram (2009), and now also serves as the foundation for the mesoscale simulation showing the behaviour of particle motion. No numerical simulation is done in the microscale. Instead, a principal sketch on colloidal and inter-particle forces is presented when discussing particles smaller than 1 µm.

1.4 Outline of the Thesis

This thesis consists of a brief summary and five appended papers. The summary gives a short description of the most important findings of the project studying 'Viscosity' found in Chapters 4 and 5. In Chapter 4, the origin of viscosity is investigated and Chapter 5 shows a possible way to measure viscosity with an on-site method studying the flow. For the sake of completeness, Section 'Numerical Methods' from Gram (2009) is included in the 'Theory' of Chapter 2. It is followed by 'Materials and Methods' and 'Experiments' with data both from the lab and numerical results. Each paper presents information of different emphasis and scaling for flow modelling and testing. Paper I is a presentation of different types of models used to simulate the flow of particles/flow of concrete. Paper II and III focus on flow behaviour in connection to plastic viscosity of the material. A simple field test for determination of Bingham parameters of concrete and micromortar is evaluated. Paper IV presents an experimental series of the micro mortar field test and an evaluation of cone crushed fines. A general overview of particle behaviour in fluid is given in Paper V.
1.5 Research Contribution

As natural resources of sand and fine material used in the concrete industry are becoming more scarce, crushed materials are being used to a greater extent. Shape and texture of machine crushed materials differ from aggregates naturally ground, layered and sorted under the course of millions of years. It is assumed that crushed aggregates are more angular and of less smooth texture than natural aggregates, see Fig 1.1, which will affect the flow behaviour of a suspension containing crushed material.

In the mix design process of cementitious suspensions, an adequate rheology of the micro mortar (all constituents in the concrete being able to pass a 0.125 mm sieve, including the cement) is crucial. The shape of fine particles is linked to the micro mortar plastic viscosity of the filler suspension including cement. The plastic viscosity here serves as an important quality assessment of the filler, since the micro mortar workability features are vital for the final mix design quality of the concrete workability.

Since the higher yield stress levels associated with the mix of crushed aggregates in the concrete may be suppressed by the addition of superplasticizers, focus of this thesis is on the connection between aggregate shape and viscosity. The mechanism of particle rotation (of fine particles, \(< 1 \mu m\)) is explained and simulation of a larger particle shows its behaviour during fluid flow. A channel flow measuring device for micro mortar and on a large scale, for concrete, is developed for on-site testing of the plastic viscosity. This will allow a quick filler assessment test in the quarry or a concrete acceptance test on the work-site rendering instant feedback on the material quality.

Figure 1.1: Difference in texture and shape between crushed and naturally rounded coarse aggregates.
Chapter 2

Theory

2.1 Rheology

2.1.1 Introduction

Panta rhei, 'everything flows' is a quote from Heraclitus (535-475 B.C.) appearing in Plato’s 'Cratylus'. The word rhei (c.f. rheology) is the greek word for 'to stream'. As stated by Malkin and Isayev (2006), rheology is the theory studying the properties of matter determining its behaviour, its reaction to deformations and flow. Structural changes of materials under the influence of applied forces result in deformations which can be modeled as superpositions of viscous and elastic effects.

2.1.2 The Bingham Model

Once a force strong enough is applied to a fluid, it flows. Newtonian fluids like honey, oil or water will continue to flow freely until the surface tension has been reached. Bingham materials like paint, Self-Compacting Concrete or cement paste will continue to flow under the influence of gravity until the yield stress has been reached. The yield stress $\tau_0$ is a threshold value that needs to be exceeded in order to move the fluid. Plastic viscosity, $\mu_{pl}$ is associated with the ease at which the material flows, or flow speed.

Figure 2.1: Simple shear.

The material of a certain thickness is sheared at a certain velocity, see Fig. 2.1
showing relative motion of material planes with simple shear rate $\dot{\gamma} = \dot{x}/h$ with height $h$ of the sample and $\dot{x}$ being the velocity of the applied force. Shear rate is the deformation intensity of the flow.

Concrete and other concentrated suspensions are often modelled as a Bingham material. It is a plastic material, showing little or no deformation up to a certain level of stress. These materials are called viscoplastic or Bingham plastics after E.C. Bingham, who was the first to use this description on paint in 1916, from Macosko (1994). The stress exerted on the material is defined as:

$$\dot{\gamma} = 0 \quad \text{for} \quad \tau < \tau_0$$
$$\tau = \tau_0 + \mu_{pl} \dot{\gamma} \quad \text{for} \quad \tau \geq \tau_0$$

(2.1)

The yield stress defines the deformability of the concrete, below this value the material does not move. As visualized by Roussel (2004), the shearing behaviour of a Bingham material can be arranged by a dashpot, a spring and the slip function, see Figure 2.2.

The spring is very stiff, $k = 10^6$ for the numerical calculations. The threshold value of the slip function is at the level of the yield stress. Once it 'breaks', the material will move according to the (plastic) viscosity of the dashpot. The slope of the function is the plastic viscosity. The stress to shear rate ratio is called the apparent viscosity, $\eta = \tau/\dot{\gamma}$. The stopping criterion of the flow for such a liquid is the yield stress.

Not used here but definitely worth mentioning is the model of Herschel-Bulkley, also used for concrete. Similar to the Bingham model, it describes the deformation of a concentrated suspension, however, assuming non-linearity of the stress equation:

$$\dot{\gamma} = 0 \quad \text{for} \quad \tau < \tau_0$$
$$\tau = m + \mu \dot{\gamma}^n \quad \text{for} \quad \tau \geq \tau_0$$

(2.2)

with $m$ and $n$ having to be determined experimentally.

The direction in three dimensions of the forces and resulting reactions of a rheological material are usually pictured as a cubic element, see Fig. 2.3:
2.2 Rheology of Incompressible Fluid with Particles

The force components can be written in the form of a matrix, called the stress tensor \( \sigma_{ij} \):

\[
\sigma_{ij} = \begin{pmatrix}
\sigma_{11} & \sigma_{12} & \sigma_{13} \\
\sigma_{21} & \sigma_{22} & \sigma_{23} \\
\sigma_{31} & \sigma_{32} & \sigma_{33}
\end{pmatrix} \equiv \begin{bmatrix}
\sigma_x & \tau_{xy} & \tau_{xz} \\
\tau_{yx} & \sigma_y & \tau_{yz} \\
\tau_{zx} & \tau_{zy} & \sigma_z
\end{bmatrix}
\] (2.3)

The stress tensor for a fluid at rest subjected to hydrostatic pressure is:

\[
\sigma_{ij} = \begin{pmatrix}
-p & 0 & 0 \\
0 & -p & 0 \\
0 & 0 & -p
\end{pmatrix}
\] (2.4)

This three dimensional cube is possibly subjected to forces in any arbitrary directions as it flows.

2.2 Rheology of Incompressible Fluid with Particles

For Pascalian liquids, meaning incompressible fluids (such as concrete), we have for the fluid velocity vector \( \mathbf{u} \)

\[
\nabla \mathbf{u} = \mathbf{0}
\] (2.5)

The governing equation for non-Newtonian fluid flow called Cauchy’s equation of motion, Malvern (1969), is given by:

\[
\rho \frac{D\mathbf{u}}{Dt} = \nabla \cdot \mathbf{\sigma} + \rho \mathbf{g}
\] (2.6)
where $g$ is the gravitational acceleration acting on the system, $\rho$ is the material density and the stress tensor $\sigma = -pI + T$. Here, $p$ denotes pressure, $I$ is the unit dyadic and $T$ is the extra stress tensor, associated with the viscosity of the fluid. For concrete being a viscoplastic material, the relation used for $T$ is according to Mase (1970):

$$T = 2\eta \dot{\varepsilon} \tag{2.7}$$

with $\dot{\varepsilon}$ being the tensor of rate of deformation as can be found in Goldstein (1996):

$$\dot{\varepsilon} = \frac{1}{2} (\nabla u + (\nabla u)^T) \tag{2.8}$$

Wallevik (2003) showed that Equation (2.6) is not only applicable for homogeneous fluids, but from a fundamental physical point of view also can be applied on coarse granular systems like fresh concrete. As defined in most rheology books, e.g. Goldstein (1996), the shear rate is

$$\dot{\gamma} = \sqrt{2\dot{\varepsilon} : \dot{\varepsilon}} \tag{2.9}$$

The factor of two in the relation of Eq. 2.7 is for historical reasons. Originally, Newton’s experiments involved only simple shear flow and it appears as the coefficient of proportionality between the shear stress component and the shear rate, Kim and Karrila (1991), i.e. $\sigma_{32} = \eta \dot{\gamma}$ as shown in Fig. 2.1.

### 2.2.1 Selected Analytical Solutions of Flow

Methods of simulation may be benchmarked in order to calibrate the model employed. One way of verifying the model is to compare it to an analytical solution. Given flow without inertia effects, meaning viscous forces are dominant, the final spread at flow stoppage is directly correlated to the yield stress of the material, assuming that material density and volume are known.

Yield stress $\tau_0$ determines spread, whereas plastic viscosity $\mu_{pl}$ is a parameter related to speed of flow. In this case, the slump flow diameter of the conventional flow test for SCC with the Abram’s cone is considered. The diameter at flow stoppage $SF$ is chosen to verify the yield stress $\tau_0$ of the concrete according to Kokado et al. (1997), and Roussel and Coussot (2005):

$$\tau_0 = \frac{225\rho g V^2}{4\pi^2(SF)^5} \tag{2.10}$$

with $\rho$ being the density of the concrete, $g$ the gravitational acceleration and $V$ the volume of concrete in the cone.

Another analytical case representing channel flow geometry is pouring concrete from a bucket into an elongated box, which will result in different spreads dependent on the yield stress $\tau_0$. Making use of the so called LCPC-box with dimensions: height = 15 cm, width = 20 cm and length = 120 cm described and experimentally validated in Roussel (2007), 6 liters of concrete are slowly poured (during 30 seconds) at one end of the box. Gently pouring will result in different spreads dependent on the yield
stress $\tau_0$. A volume of 6 liters is approximately 1000 or even 4000 times the volume of the largest particle in the concrete, thus this amount is sufficient to be representative for the material Roussel (2007). Once the density $\rho$ of the concrete is known, the yield stress can be determined according to Equations (2.11) and (2.12). With $w$ being the channel width and $h_{\text{max}}$ the maximum height of the poured concrete in the channel, the tested volume $V$ will be equal to, Roussel (2007):

$$V = w \int_0^{h_{\text{max}}} xdh = \frac{w^4}{4A} \left( \ln(1 + u) + \frac{u(u - 2)}{2} \right)$$

with $A = \frac{2\tau_0}{\rho gw}$ and $u = \frac{2h_{\text{max}}}{w}$. (2.11)

The maximum height $h_{\text{max}}$ of the concrete at the pouring end of the channel can be linked to spread length $l$ at flow stoppage, Roussel (2007):

$$l = \frac{h_{\text{max}}}{A} + \frac{w}{2A} \ln \left( \frac{w}{w + 2h_{\text{max}}} \right)$$

For the theoretical solution of $\tau_0$, inertia effects of the material are disregarded and a non-slip condition is assumed.

2.3 Particle Packing and Concrete Workability

2.3.1 Introduction

About 1900, a Frenchman, Feret developed relationships between the quantities of cement, water and air voids, as can be read in Meininger (1982). He was first to state scientific principles for proportioning. Fuller and Thompson (1907) published their 'Laws of Proportioning Concrete', including the well-known 'Fuller Curve' for aggregate grading of maximum density. Generally, a better (but not necessarily denser) packing system of aggregates, an adequate proportioning, results in better workability of the fresh concrete as well as increased durability for the hardened concrete. Conventional concrete has a higher amount of coarse aggregates compared to SCC. Included aggregates can be packed more densely, since stiffness or ‘jamming’ may be easily loosened up with a poker vibrator. If vibrated too much, segregation of particles and water will occur. SCC is particularly sensitive in that sense, since it is highly flowable. The paste and mortar contents need to be higher for SCC, in order to keep aggregate particles apart to reduce friction between them. Adequate packing and paste content will maximize workability as well as durability. Kennedy (1940) states that the consistency of concrete is related to two factors: the consistency of the paste and the amount of excess paste between the particles. According to Andersen and Johansen (1993), an unsatisfactory gradation of sand and coarse aggregate may lead to:
- Segregation of the mortar from the coarse aggregates.
- Bleeding of water below and around larger aggregates and on the surface of the concrete.
- Settling of aggregates, leaving paste on the top layer of the concrete.
- Need of chemical admixtures in order to restore workability of the concrete.
- Increased use of cement.
- Insufficient air entrainment and air-void distribution.

For settling and segregation of aggregates to be avoided, the aggregates must be sufficiently supported by the surrounding fluid. The buoyancy of the particle, $B$, and the particle flow resistance $F_d$ should be in equilibrium the particle weight, $G$ in order to avoid settling. For a particle at rest in a fluid, we get

$$F_d = G - B$$

where $r$ is the particle radius, $\rho_f$ and $\rho_p$ the density of the fluid and the particle respectively, and $g$ is the gravity acting on the system. As early as 1851, Stokes derived an expression for this frictional force acting on a sphere at laminar flow ($Re << 1$, see Section 2.4.2) in a Newtonian fluid: $F_d = 6\pi \eta v$ with sphere velocity $v$ and apparent viscosity $\eta$. Apparent viscosity $\eta = \tau_0/\dot{\gamma} + \mu_{pl}$ and shear rate is set to be $\dot{\gamma} = v_t/d$ with $v_t$ denoting the so called terminal velocity reached by the sphere as dynamic forces reach equilibrium, $v \rightarrow v_t$. For a non-segregating SCC, the following criterion holds:

$$G \leq B + F_d \quad (2.14)$$

With the Newtonian expression for $F_d$ as shown in Paper V, it is obtained that $d_{max} = \frac{18\tau_0}{g \left| \rho_p - \rho_f \right|}$ as shown in Section 4.3, Eq. (4.2). Micro mortar tests performed at CBI, Golubeva et al. (2014) and an experimental study by Bethmond et al. (2003) confirm this equation for the maximum particle diameter, also found in Shen et al. (2009) and Roussel (2006). The risk of segregation decreases as $\tau_0$ holds a high value and as the density difference between the particle and the surrounding fluid decreases. Since a high value of $\tau_0$ results in less deformability, one should opt for a sufficiently low $\left| \rho_p - \rho_f \right|$. Micro particles diffuse in water, supporting small particles forming a mortar phase holding slightly bigger aggregates. Obviously, an optimized grading of the aggregates ensures proper workability.

Different optimization theories exist when deciding on grading curves for the concrete, there are packing theories, design procedures especially for SCC as well as different blocking criteria.

### 2.3.2 Maximum Particle Packing

An Appolonian Circle Packing, APC, (after Appolonius of Perga, 262-190 B.C.) is an ancient Greek construction by repeatedly inscribing circles into the curvilinear triangular interstices formed by three kissing circles, Fuchs (2010). The inscribed
circles belong to the next generation of circles, an infinite number of generations will result in maximum packing density, \( \Phi_{max} = 1 \), see Fig. 2.4.

Packing and packing rate of particles constitute another way to define particle quality. Particle packing has quite a long history and is widely used in the field of geotechnology. The models described here are based on the assumption of no attracting or repellent forces between particles. Particle packing optimization is a common way to design a concrete recipe. The voids between the aggregates are filled with cement matrix. Minimizing the voids will consume less cement paste. Unless particle packing has been optimized, workability will be affected in a negative way. Random (loose or poured) packing of monosized perfectly shaped spheres gives a packing ratio of approximately 62.5 %. Placing the spheres one by one instead to create a maximum packing grade will give a much denser packing. Such a virtual packing grade is defined by de Larrard (1999) as the perfectly attainable packing/placing of aggregates as possible. The span of particle sizes included in the mix as well as how well the particles fit into one another affect the packing density. Other parameters that affect the packing density are shape and surface roughness of the particles. Flaky and elongated/rodlike particles may be compacted to a much higher extent than rounded particles and thus filling more voids. It is interesting to note that the flaky and rodlike aggregates instead produce a quite porous packing when random/loose packing is applied. For loose packing, perfect spheres render the highest packing rates whereas other aggregate shapes result in more porous packing rates. For monosized particles of the same surface roughness (friction coefficient), loose packing as well as hard packing values are determined by particle shape.

As described by Larsén (1991), a historical packing model was developed by C.C. Furnas, whose model is used today in different modifications. For a three phase (or class) system, the model states the maximum packing efficiency, \( PE_{(max)} \), to be:

\[
PE_{(max)} = PE_c + (1 - PE_c) \cdot PE_m + (1 - PE_c) \cdot (1 - PE_m) \cdot PE_f
\]  

(2.15)

where \( PE_c, PE_m \) and \( PE_f \) are particles in the ranges coarse, medium and fine,
respectively. The packing efficiency is defined as the ratio of material volume and the total volume available. For particles with a large size difference in different classes, Furnas’ model estimates an almost exact packing density, Roussel (2012). However, this model is not so efficient to describe a continuous curve of particles. A number of particle packing models were developed over the past 70 years. Not all models are suitable for concrete mix constituent proportioning. Below, two models are presented that aim at proportioning concrete by finding the minimum voids ratio.

A packing model that takes many sizes and different shapes into consideration was developed by de Larrard (1999), aiming at proportioning concrete by finding the minimum voids ratio. His Concrete Mixture Proportioning model, the compressible packing model (CPM), makes use of the concept of ‘virtual packing’, \( \chi \). By virtual packing is meant the highest possible packing density, as if the aggregates were placed optimally one by one. In actuality, we always have a random packing, resulting in extra space that could be filled by a smaller fraction. The virtual packing density of a mix of monosized spheres is equal to \( \frac{\pi}{3\sqrt{2}} \approx 0.74 \), while the physical packing density that can be measured in a random mix is close to 0.64 as stated by Cumberland and Crawford in 1987, according to de Larrard (1999). The model of de Larrard (1999) is described by the following: a class \( i \) is a fraction of more or less monosized particles. This class is represented by the log mean \( d_i \), and arranged in a sequence such that \( d_i > d_{i+1} \).

Each polydisperse mix can be simplified into a binary mix by looking at just the largest (first) class as being submerged into a dominant, finer class. Zooming into the second class, again, its largest particles are submerged into an even finer class. The eigenpacking density \( \beta \) is experimentally determined for each material or class. Every combination or mix of packed particles always has a so called dominant class, which keeps it packed and prevents it from flowing, see Fig. 2.5. The virtual packing grade of this class in the particular mix is equal to the virtual packing grade of the total mix.

![Figure 2.5: Different dominant fractions: fine and coarse (with segregation).](image)

Since the virtual packing grade cannot actually be achieved, de Larrard introduces a so called \( K \)-value. This value represents the energy put into packing the aggregates. The virtual packing density would require an infinite amount of energy to achieve \( (K=\infty) \). A value of 9.0 for \( K \) is equivalent to vibration and compression of 10 kPa,
whereas $K=4.1$ is equivalent to just pouring the mix, 4.5 is for dry rodding. The sum of all $K$ values of each class gives a $K$ of the total, where an extremely dense compaction can be obtained. The model is quite accurate and works well for crushed aggregates also, de Larrard (2007). For a calibration of the eigenpacking value of class, it is compacted at a known $K$-value resulting in a packing density $\beta$. In a monodisperse mix, we have

$$K = \frac{1}{\beta/\Phi - 1} \quad (2.16)$$

This allows the calculation of $\beta$ for a known value of $K$. For different compaction index $K$, a different calibrated $\beta$ can be expected.

The $K$ value of the total, is the sum of all $K$ values in each class of the total mix:

$$K = \sum_{i=1}^{n} K_i \quad (2.17)$$

$K_i$ of class $i$ is obtained by a function of the solid volume ($\Phi$), its volume fraction related to the total solid volume (called $y_i$), $\chi_i$ and the residual packing density of the class, $\beta_i$.

$$K = \sum_{i=1}^{n} K_i = \sum_{i=1}^{n} \frac{y_i \beta_i}{\beta_i - 1} \quad \Phi - \chi_i \quad (2.18)$$

The virtual packing can be calculated from a relation to the volume fraction of each class and $\beta_i$, taking grain interaction effects ($a$ and $b$) into account.

$$\chi_i = \frac{\beta_i}{1 - \sum_{j=1}^{i-1} y_i (1 - \beta_i + b_{i,j} \beta_i (1 - \frac{1}{\beta_j})) - \sum_{j=i+1}^{n} y_i (1 - a_{i,j} \beta_i \beta_j)} \quad (2.19)$$

with the grain interaction parameters having been experimentally determined to be:

$$a_{i,j} = \sqrt{1 - (1 - d_j/d_i)^{1.02}} \quad b_{i,j} = 1 - (1 - d_j/d_i)^{1.5} \quad (2.20)$$

with $d_i$ and $d_j$ as the mean diameters of aggregates of classes $i$ and $j$.

For a predetermined $K$ and known $\beta_i$ and $\chi_i$, the above equation can be solved to maximize for different $y_i$ in order to obtain the minimum voids ratio. It is assumed that the mixture leading to the optimum actual packing density is the same as the one giving the optimum virtual packing density. The minimum virtual and actual porosities then become respectively:

$$\pi_{min} = (1 - \beta)^n \quad (2.21)$$

$$p_{min} = \left(1 - \frac{\beta}{1 + n/K}\right)^n \quad (2.22)$$
with \( n \) being the number of classes. A number of features are added to this model, mixes can be calculated including for example fibres, de Larrard (1999). De Larrard’s method is also suitable when particles are gap graded.

It was found, that the mix proportioning models minimizing the void ratio produce rather harsh concrete mixes. It is necessary for fresh concrete to flow, at least to a certain degree. In case all particles are completely packed, flow is highly unlikely, especially when including crushed aggregates. An approach to reduce the coarse/fine aggregate ratio is necessary.

2.3.3 Optimal Packing by Particle Distribution

Proportioning from a Dimensioning Point on the Sieve Curve

Once the particle distribution is known to be continuous, and once the packing efficiency PE for the whole mix is not less than the lowest PE included (this would be a suspension), the slope of the sieve curve as well as one single point on the curve may be identified to determine the proportioning, called \( y_0 \) by Alexandersson and Buö (1970). This method has traditionally worked very well in Sweden, since aggregates from eskers are naturally rounded as well as favourably graded and packed.

For workability reasons, the Fuller curve, Fuller and Thompson (1907), stating a relation between aggregate size and amount, is commonly used. The Fuller curve ensures continuous grading, most favourable are naturally rounded aggregates for concrete workability. The Fuller curve is described by:

\[
P(D) = \left( \frac{D}{D_{\text{max}}} \right)^q
\]

with \( q = 0.5 \) and where \( P(D) \) is the fraction \( P \) that can pass the sieve with the opening \( D \), \( D_{\text{max}} \) is the maximum particle size of the mix. The Fuller curve does not give the maximum packing density, but allows some space for the concrete to move. The packing grade and particle size, shape and type of mineral is all part of what defines the concrete features and flowability.

Andreassen and Andersen presented a semi-empirical study regarding the packing of granular materials, found in Andreasen and Andersen (1930). According to their study, the optimum packing of fines is achieved when \( q \approx 0.37 \).

In general, the more powders in a mix (\(< 125 \ \mu m\) ), the smaller the \( q \) that best characterizes the particle size distribution. The Andreassen and Andersen curve, prescribing a grading of particles down to a size zero was modified by Funk and Dinger (1994), introducing a minimum diameter, which in actuality is more adequate. They were able to make coal-water slurries with a coal content of 80 \% and with viscosities of about 300 mPas. This shows an increased workability for an optimized packing density. The better the packing, the more water is available to act as a lubricant for the solids, and the better is the workability.
The most workable concrete is obtained by optimizing the granular skeleton, especially for the fines, including the effect of cement according to Vogt (2010). The modified Andreassen equation reads:

\[ P(D) = \left( \frac{D_q^q - D_{\text{min}}}{D_{\text{max}}^q - D_{\text{min}}^q} \right) \]  

(2.24)

According to Powers (1968), Feret separated continuously graded material into three aggregate fractions and by experiments concluded that the smallest possible void content for the given range was reached when the intermediate range was omitted. Similarly, Furnas also stated that the most compact packing would result from mixing two widely different sizes. However, this was doubted by Andreasen and Andersen (1930), stating that one can hardly expect greater density from products consisting of fewer fitted sizes than from products in which all sizes are present. Furthermore, the grading span will determine minimum porosity for an optimized packing of perfect spheres with no friction. An example of the Andreassen and Andersen, the modified Andreassen curve with \( q = 0.37 \) and the Fuller curve is shown in Fig. 2.6. Besides an optimal packing of the aggregates, optimization of water requirement is fundamental for rheological parameters of SCC according to Marquardt et al. (2002).

2.3.4 Random Loose Packing

Concrete mixes based on the idea of loosely packed aggregates, whose voids can be filled with micro mortar (a two-phase system) should also display adequate workability giving that the mortar rheology is adequate and the packing of aggregates 'loose enough'. Factors decreasing the Random Loose Packing, RLP, grade are aspect ratio, angularity and surface roughness. These same factors also increase the water demand, more paste is needed for the two-phase system. It was suggested for ellipsoidal particles that more paste is required for them to move and rotate in the
suspension, Gram (2003). The same theory was also presented by Lagerblad (2005) and mentioned in Westerholm (2006). A very strong correlation between particle aspect ratio and RLP was found for particles in the range 63 – 125 \( \mu \)m. For fine material type found in Table 4.1., cone crushed particles of different mineralogical origin, the aspect ratio (obtained by analyzing aspect ratio of samples with a SEM) differs between 2.15 (Crystalline Dolomite) and 4.50 (Granite type with 42.5 % mica content).

Values of aspect ratio are also compared to the RLP of a perfect sphere, see Fig 2.7. Averaged values were obtained by image analyzing ca 1000 particles to obtain their individual aspect ratio. The sum of all aspect ratios was divided by the number of particles. A strong correlation was found between loose packing of a material and the resulting viscosity when mixing the material in a suspending fluid. For the case of a 23.8 % (by volume) concentration in a cement paste mix, this correlation is shown in Fig. 2.8.

This shows that loose packing is an adequate method to characterize grain shape in a (almost monosized) fine material, 63-125 \( \mu \)m, and that it gives a good indication as to the relative viscosity obtained by the suspension and of the average aspect ratio of a sieved material. RLP here seems to prove itself to indicate workability.
of its suspension. The grading curve alone is not sufficient information for the characterization of its suspensoidal rheological properties according to Gram et al. (2014).

2.4 Numerical Methods

This section is restricted to the theory of the Distinct Element Method, and Computational Fluid Dynamics, CFD, which were employed to model mortar and concrete flow by the author. For both types of numerical methods, it holds true that in the system calculated:

i) energy is conserved,

ii) mass is conserved and

iii) Newton’s second law: \( F = m \cdot \ddot{x} \) is applicable.

For an overall review of methods and research in the field of numerical simulation of concrete flow, please see Roussel and Gram (2014) for an extensive presentation of some previous work.

2.4.1 The Distinct Element Method, DEM

The Distinct Element Method, DEM, models the movement and interaction of particles. It allows displacements and rotations of discrete bodies, that may attach or detach from each other. This method was originally developed as a tool to perform research of the behaviour of granular material. A fundamental assumption of the method is that the material consists of separate discrete particles (not necessarily spherical). Forces acting on each individual particle are computed according to relevant physical laws. Then, physics are added up to find the total force acting on the particles. An integration method is employed to compute new particle positions from applied forces according to Newton’s laws of motion. The new positions are used to compute the forces for the next time-step, looping until the simulation ends. The displacements and rotations of the particles are calculated according to the following governing equation

\[
F_i = m(\ddot{x}_i - g_i) \tag{2.25}
\]

The translational motion of the center of mass of each particle is described in terms of position \( x_i \), velocity \( \dot{x}_i \) and acceleration \( \ddot{x}_i \); the rotational motion of each particle is described in terms of its angular velocity \( \omega_i \) and its angular acceleration \( \dot{\omega} \). These equations of motion are integrated using a centered finite difference procedure. Velocities and angular velocities are calculated halfway through the time step at \( t \pm \Delta t/2 \), \( \Delta t \) being the size of the step. Displacements, accelerations, angular velocities, forces and moments are computed at the primary intervals of \( t \pm \Delta t \). The accelerations are calculated as

\[
\ddot{x}_i^{(t)} = \frac{1}{\Delta t} (\ddot{x}_i^{(t+\Delta t/2)} - \ddot{x}_i^{(t-\Delta t/2)}) \tag{2.26}
\]
\[ \dot{\omega}_i^{(t)} = \frac{1}{\Delta t}(\omega_i^{(t+\Delta t/2)} - \omega_i^{(t-\Delta t/2)}) \]  

Inserting the above expressions into the governing equations for particle velocities and angular velocities we get:

\[ \dot{x}_i^{(t+\Delta t/2)} = \dot{x}_i^{(t-\Delta t/2)} + \left( \frac{F_i^{(t)}}{m} + g_i \right) \cdot \Delta t \]  

\[ \omega_i^{(t+\Delta t/2)} = \omega_i^{(t-\Delta t/2)} + \left( \frac{M_i^{(t)}}{I} \right) \cdot \Delta t \]

where \( M_i \) is the resultant moment acting on the particle. Finally the obtained positions are updated according to:

\[ x_i^{(t+\Delta t)} = x_i^{(t)} + \dot{x}_i^{(t+\Delta t/2)} \Delta t \]

The Distinct Element Method is quite computer processor intense with long computer sessions. Another limit of the method is the number of particles used in the computation. An alternative to calculating forces and movements on all the particles individually, could be to calculate an average force on several particles and treat the material as a continuum. Forces on a molecular level between particles that could be simulated are for example the Coulomb force, Pauli repulsion and van der Waals force. In macroscopic simulations, the following forces may be simulated: gravity, damped or hard particle interactions, friction, cohesion and adhesion. The computational cost increases as the particle-particle interaction is made more complex.

### 2.4.2 Computational Fluid Dynamics, CFD

Historically, fluid mechanics has relied on pure experiment or pure theory since the publication of Sir Isaac Newton’s ‘Principia’ in 1687. Today, since the 1950’s and 60’s, Computational Fluid Dynamics, CFD, supports and complements both experiment and theory, Wendt (1992). With the advent of the high-speed digital computer and its constant evolving in speed and efficiency, numerical simulation of flow is here to remain as the third dimension of fluid dynamics.

In fluid mechanics, usually the Reynold’s number \( (Re) \) is used to characterize the type of flow. Flow may creep around e.g. a spherical object \( (Re << 1) \), it may be laminar, transient or turbulent. The Reynold’s number must be equal for two cases with the same dynamic similarity in which viscous effects are important, Kundu and Cohen (2004), as is the case for SCC flow. The Reynold’s number is a dimensionless quantity defined as:

\[ Re = \frac{\rho \dot{\gamma} g^2}{\eta} \]

where \( \eta \) is the apparent viscosity and \( g \) is the characteristic length scale, meaning the hydraulic diameter or hydraulic radius.
Originally, the equations by Navier-Stokes referred only to the governing momentum equations, but has today expanded to the meaning of the complete system of governing equations: continuity, energy and momentum, Wendt (1992). To date, there is no general closed-form solution to the coupled system of governing equations. The non-linear Partial Differential Equations (PDEs) are very hard to solve analytically, Wendt (1992). The PDEs may be discretized using several methods, the Finite Volume technique and Finite Element Method being two of them.

### Finite Volumes

The Finite Volume technique presents and evaluates Partial Differential Equations, PDEs, as algebraic statements. PDEs are associated with problems involving functions of several variables, such as fluid flow and elasticity. The values to be obtained are calculated on a meshed geometry. Finite volume refers to a control volume representing a reasonably large, finite region of the flow. The fundamental physical principles are applied to the fluid inside the control volume, Wendt (1992). In this piece of work, Volume of Fluid, VOF, method is employed as the interface tracking method for a multiphase model. VOF (Hirt and Nichols (1981)) tracks the interface using a phase indicator marker $\xi$ such that in a control volume, $\xi = 0$ only phase one is represented and $\xi = 1$ only phase two is represented. $0 < \xi < 1$ represents an interface in the control volume. The scalar $\xi$ is the volume fraction moving, the fluid properties vary in space according to the volume fraction of each phase:

$$
\rho = \rho_1 \xi + \rho_2 (1 - \xi) \\
\mu = \mu_1 \xi + \mu_2 (1 - \xi)
$$

(2.32)

Every cell holding a $\xi$ value carries a marker, such as a distinct colour. The phase interface does not remain a sharp area, but diffuses into a region where further refinements are made compared to the regions denoted with natural numbers $\xi = 0$ or $\xi = 1$.

### Finite Elements

The Finite Element Method, FEM, originated from the need for solving complex elasticity and structural analysis problems in civil and aeronautical engineering. The method is a numerical procedure for analyzing structures and continua. FE procedures are used to analyze problems of stress analysis, but also of heat transfer, fluid flow, lubrication, electric and magnetic fields etc. In FEM, a continuous domain is discretized into a set of discrete sub-domains called elements, Cook et al. (1989). FEM is a good choice for solving PDEs over complex domains.
Chapter 3

Material and Methods

In this Chapter, materials for the experiments are described. Commercially available products were used, except for the cone crushed fillers, details about the fillers are to be found in Table 4.1. Laboratory methods of the different methods are summerized briefly and methods on numerical simulation are presented.

3.1 Material

Micro mortars presented in the thesis consist of water, cement and mostly a filler material. Some of the fine material was crushed, it is presented in Table 4.1.

3.1.1 Materials

Powders

A Swedish cement type CEM II/A-L 42.5 R from Cementa AB was used in the micro mortar experiments. The cement is coground with limestone, giving a limestone content of approximately 13 weight percent. The density of CEM II is $\rho = 3080$ kg/m$^3$. For the concrete mixes presented in Paper II, two additional types of cement were used: A Swedish cement type CEM I 42.5 R MH/SR/LA from Cementa AB. The density of CEM I is $\rho = 3200$ kg/m$^3$. A Danish cement type CEM I 52.5 SR/LA from Aalborg Portland, a low alkali and sulphate resistant white portland cement was used.

In some mortar and concrete mixes, Limestone filler L25 and L40 from Nordkalk AB were included. They consist of crushed crystalline limestone (CaCO$_3$).

Fines presented in Paper IV and in Table 4.1 were all cone crushed on the quarry site. They are sieved down to the fraction $63 - 125 \mu$m according to ASTM C 117 (2003). As seen in Table 4.1, not all fillers were removed.
Aggregates

For concrete mixes in Paper II, natural glaciofluval granitoid fine aggregates (0-8 mm) and coarse aggregates (8-16 mm) were used. All aggregates are of Swedish origin.

Superplasticizers

A polycarboxylate-based ether type of superplasticizer (Glenium 51) from BASF was used with a dry content of 35 percent.

3.1.2 Laboratory Methods

Fine Material (63-125 µm) Characterization

Random Loose Packing, RLP, of the fine material is obtained by gently pouring of the material into a funnel leading the powder on a vibratory feeder (Retsch DR 100). The material is allowed to deposit in a copper cylinder of 85 mm height, holding 100 ml of material. The loose packing is performed according to SS-EN 1097-3 (1998).

Aspect ratio is per definition the ratio between the major and the minor axis of the ellipse equivalent to the object. This was determined in the SEM using an image analyzer on prepared samples of fine material in thermosetting plastic. Point counting thin sections (300 points) gives an overall mineralogical content of the material, Beyer and Riesenberg (1988). Particle size distributions were determined according to ISO 13320 (2009) method ER 9322 at Cementa in Slite on a Malvern Mastersizer 2000 with Malvern Hydro 20006 addition for the dispergation. The theory of Mie is applied. The specific BET surface by Brunauer et al. (1938) is obtained by method CR 0506 in the laboratory of Cementa. A Micrometics Gemini 2375 is set for five pressure points with Helium, He2, to determine the free space and nitrogen, N2, to obtain the adsorption value.

Workability

Slump flow was tested and digitally recorded. The Abram’s cone final slump flow diameter was measured according to SS-EN 12350-8 (2010). For blocking tests, the J-ring (diameter 300 mm) may be placed outside the Abram’s cone before lift, in order to measure how well the concrete passes rebars. 18 mm thick rebars are symmetrically placed on the ring (their number can be 16, 18 or even 22), the height of the concrete is measured before and after the rebars, SS-EN 12350-12 (2010), speed of flow as well as final slump flow diameter were recorded.
The L-box was tested and simulated according to SS-EN 12350-10 (2010), however without rebars. Flow speed was recorded and simulated. The reader may also refer to e.g. De Schutter et al. (2008) for more details on the SCC test methods. A sensitivity analysis of slump flow and L-box test methods can be found in Emborg et al. (2003).

Into the LCPC-box, with dimensions height = 150 mm, width = 200 mm and length = 1200 mm described and experimentally validated by Roussel (2007), 6 liters of concrete are slowly poured (during 30 seconds) at one end of the box. Once the density and final spread of the concrete are known, the yield stress can be determined according to Equations (2.11) and (2.12). The reader is referred to Section 2.2.1 and Roussel (2007) for more information on the LCPC-box.

The rheological measuring device, the Rheo-box is built in different sizes, for concrete and for micro mortar measurements. The geometry of the box is described in Section 5.4, also see Fig 5.2. A camera mounted straight above the measuring box is capturing the flow propagation of the released fluid. Gate opening time has been excluded from the duration of flow propagation by starting the clock at the first visible fluid exiting the gate. In addition to filming the spread in the channel and charting its propagation, time \( t_x \) for the spread to reach a set distance from the gate \( X \) is recorded as well. Final spread length \( \ell \) is measured from the container gate to the center of the front line after flow stoppage. Open channel flow is utilized in favour of a rheometer to obtain plastic viscosity for very thick paste mixes.

Rheology

Rheology of the micro mortar was measured with a Physica MCR300 rheometer. Concrete rheology was measured with a ConTec-4 SCC, ConTec wide gap viscometer and evaluated according to the Bingham model. The particular velocity profile of the outer cylinder for the shearing sequence used during measurements is thoroughly described by Westerholm (2006).

3.2 Numerical Simulation

3.2.1 PFC

\( \text{PFC}^{3D} \) by Itasca Consulting Group, Inc. (https://www.itascacg.com), models movement and interaction of spherical particles by the Distinct Element Method. It is designed to be an efficient tool to model complicated problems in solid mechanics and granular flow. Particles may attach to one another through bonds (hard or soft). Particles may also be clumped together, forming unbreakable so called
super-particles to form arbitrary shapes as shown in Figure 3.1.

![Image](image_url)  
Figure 3.1: Forming so called super-particles with unbreakable bonds to the left, regular particle bonds can break once stress/strain exceeds their strength, to the right.

A special COMMAND language embedded in so called PFC FISH functions is used to generate particles, walls, initiate velocities, define bonds, etc. For the specific Bingham model used here, a User Defined Model (UDM) was implemented. While the original code of the software remains opaque, the user may access C++ pointers to modifiable PFC functions for friction, bonds, contact forces and velocities as well as particle positions. This allows the creation of e.g. packing algorithms and contact models.

In order to obtain an adequately loose packing, the particles are generated at random positions within a predefined area. Under the influence of gravity, the particles can be guided to their container through a funnel or similar, Petersson and Hakami (2001). In cases of monosized spheres, careful packing could result in crystallization of the particle collection, giving a structure that will not flow. Best results are obtained with different particle sizes, the size should differ at least $\pm 25\%$.

No straightforward connection between the rheological parameters of the modeled material and the inter particle forces was found. Some correlation between values of the slip function and the dashpot could be observed. Most of the material characteristics are determined by the shape of a non-linear spring function governing particle to particle contacts in the normal direction, Gram (2009). A steeper slope of the spring constant (higher inter-particle forces) results in a smaller slump flow.

### 3.2.2 OpenFOAM

The OpenFOAM (Field Operation And Manipulation) code is an object-oriented numerical simulation toolkit for continuum mechanics written in C++, released by OpenCFD Ltd and available for free (https://www.opencfd.co.uk). It is a large CFD library with different types of solvers running on Linux or Unix Operating Systems. This finite volume solver with polyhedral mesh support calculates the mass and momentum equations in their discretized form, which guarantees the conservation of fluxes through the control volume. The code is transparent and may be altered and enhanced with add-ons by the user.
3.2. NUMERICAL SIMULATION

The fluid simulated represents a homogeneous material, in this case the concrete. Effects of particles in the concrete are not accounted for here. Bingham viscosity given by Eq. 2.1 will render a singular point for zero shear rate (rigid body), which will lead to infinite apparent viscosity. This is avoided by introducing the following equation for the numerical simulations suggested by Papanastasiou (1987):

\[ \eta = \mu_{pl} + \frac{\tau_0}{\sqrt{2\dot{\varepsilon} : \dot{\varepsilon}}} \left[ 1 - e^{-k\sqrt{2\dot{\varepsilon} : \dot{\varepsilon}}} \right] \]  

(3.1)

The value for \( k \) is a very large number, \( k = 5000 \) for simulations shown. Eqs. 2.5 to 2.9 together with Eq. 3.1 together define the non-compressible viscosity model for the numerical simulations. The material model is verified and compared to analytical solutions (according to Eqs. 2.10 to 2.12) for both slump flow and the LCPC-box and two different levels of yield stress as seen in Figure 3.2.

The numerical model and the analytical solution differ no more than 3 % at flow stoppage, as described in Gram (2009). These examples are meant to convince the reader that the numerical Bingham model is representative for concrete spread at flow stoppage also for other geometries. It is suitable to model form filling, air inclusions and blocking due to poor workability, Gram (2009).

Solver for multi-Phase Flow

OpenFOAM solvers are always 3D. A 2D case can be created employing empty boundaries. The solver used for 'free surface flow' of concrete called interFoam is specifically tailored for incompressible (liquid) interface tracking of laminar fluid.
flow. The VOF method described in Section 2.4.2 is not actually a free surface method, but a two fluid approach. Since the phase interface does not remain a sharp area, a slight diffusion is noticeable after a few time steps. This diffusion can be corrected between the numerical time steps by employing software to round the phase indicator marker $\xi$ either up or down to the nearest natural number (depending on which material dominates the volume). This procedure results in a slightly compressed (both shorter and wider) particle at the end of flow (see Fig. 4.3) as can be noticed by the detail-oriented reader. The principal behaviour and particle orientation during flow are not affected by this diffusion.

The standard finite volume discretization selected is Gaussian integration with a linear upwind interpolation scheme. A so called PISO (Pressure Implicit with Splitting Operators) algorithm is employed for the calculations. It is based on the assumption that the momentum discretization may be safely frozen through a series of pressure correctors, which is true only at small time-steps. For this reason, this algorithm is sensitive to mesh quality. To ensure convergence of certain PDEs used by OpenFOAM, the so called Courant number, $Co$, should be below 1 at all times. It is defined as

$$Co = \frac{\Delta t |u|}{\Delta x}$$

where $\Delta t$ is the time step, $|u|$ is the magnitude of the velocity through the element and $\Delta x$ is the size of the element in the direction of the velocity. Since the flow varies across the domain, $Co < 1$ must be ensured everywhere, OpenFOAM (2008).

### 3.2.3 femLego

An in-house software from the Mechanics Department at The Royal Institute of Technology (KTH) in Stockholm, called femLego, Amberg et al. (1999) was used to simulate a falling of a cylinder in an incrompressible Newtonian liquid (oil). The Finite Element Method was employed in 2D with a uniform quadratic mesh with 91 x 451 nodes. This FEM application is based on a discretization method which is of first order in time and space. The mesh is uniform and could not be subducted to changes locally. Hence, to improve the accuracy of the computations, a streamline diffusion was introduced. Streamline diffusion has the same idea as artificial viscosity, which smears out (diffuses) the large gradient, thus giving a smooth solution, Wendt (1992). Keeping in mind that the method is of the first order, the value of the iteration step in the computations was kept quite low, $\Delta = 10^{-4}$. Two of these simulations are shown in Article I and V and in Gram (2009).
Chapter 4

Viscosity I: Particle Motion in Fluid

4.1 Summary of Finding

Numerical simulation has shown that an elongated particle will align its major axis with the direction of flow. The centre of the particle follows the fluid flow along the streamlines. Finer particles may rotate between the larger particles moving at different velocities or once the streamlined flow is not linear, as in corners and bends. The rotation of crushed, non-spherical finer particles as well as rotating particles that agglomerate leads to an increased viscosity of the fluid.

4.2 Historical Notes

The study of particles in fluid has been conducted for over a century. One single sphere suspended in fluid is subjected to a downward gravitational force $G$ as well as an upward buoyant force $B$. Once the particle density, $\rho_p$, differs from the density of the fluid, $\rho_f$, a force is exerted on the suspended sphere: 

$$G - B = \pi d^3 g (\rho_p - \rho_f) / 6$$

The particle diameter is denoted $d$. As early as 1851, Stokes derived an expression for the frictional force acting on a perfect sphere when moving in a Newtonian fluid. This frictional force, called drag force $F_d$, is defined as 

$$F_d = 3\pi \eta dv,$$

with sphere velocity $v$ and Newtonian fluid viscosity $\eta$. This equation holds true for laminar flow with very small Reynold numbers ($<< 1$).
Later Einstein studied the sphere addition effect on fluid viscosity published in 1906 and 1911, Macosko (1994). His theory on the viscosity $\eta$ of an incompressible Newtonian liquid subjected to creeping flow when adding density neutral spheres still holds: $\eta = \eta_f (1 + 2.5\phi)$ with subscript $f$ referring to the fluid without the addition of spheres and $\phi$ denoting the particle concentration. This holds true for a sufficiently small particle volume of less than 5 percent, with no interaction between the particles. Since then, a crowding factor was introduced and Krieger and Dougherty (1959), presented an equation for the evaluation of denser particle concentrations including non-spherical particles and their effect on fluid viscosity:

$$\eta = \eta_f (1 - \phi/\phi_{max})^{-[\eta]_{max}}.$$  

The intrinsic viscosity $[\eta]$ varies according to particle shape. It was calculated to be 2.5 for perfect spheres by Einstein and will be of greater value for non-spherical particles, Scheraga (1955), as seen in Fig. 4.1.

### 4.3 Falling Particle in Fluid

The particle subjected to Stokes’s drag force is moving at an increasing velocity, until the drag force and the difference between gravity and buoyancy reach equilibrium $F_d = G - B$ and a so called terminal velocity $v_t$ is reached Struble and Sun (1995). For a plastic non-Newtonian fluid modeled as a Bingham material with $\eta = \tau_0/\dot{\gamma} + \mu_{pl}$ and shear rate $\dot{\gamma} = v_t/d$, the steady state terminal velocity is easily deduced as $v \rightarrow v_t$:

$$v_t = \frac{d}{\mu_{pl}} \left( \frac{dg | \rho_p - \rho_f |}{18} - \tau_0 \right)$$  

(4.1)

No movement of the particle occurs at yield stress $\tau_0 \geq (dg | \rho_p - \rho_f |) / 18$. Similarly, the maximum particle diameter, which can be held by the yield stress, is derived by
In the case that \( \rho_p > \rho_f \) and \( \tau_0 = 0 \), a settling non-spherical particle will orient itself facing the direction of movement with its least cross-section to be subjected to the least resistance possible, minimizing the torque on the particle that is exerted by the surrounding fluid. The case of the falling ellipsoid was simulated with different starting position angles and was found to always align its major axis with the direction of movement.

4.4 Fines in Fluid

It is known that particles of a few microns or less in size, exhibit a random Brownian motion when suspended in a fluid. This motion allows the particles to diffuse through the liquid and according to Krieger and Dougherty (1959), Brownian movement causes concentration fluctuations. This results in pairs of particles whose distance is small, in the order of one diameter. Once particles get close to each other, inter-particle attractive forces (van der Waals forces) may contribute to the agglomeration of two or more particles. Two agglomerated particles are called a doublet. At infinite shear rate, all doublets will be dissociated. For low shear and high-concentration mixes, triplets and even higher multiplets interactions become increasingly important.

4.5 Numerical Experiment

A small, L-box like device was modeled numerically with OpenFOAM as a Bingham fluid (yield stress \( \tau_0 = 44 \text{ Pa} \) and plastic viscosity \( \mu_{pl} = 0.22 \text{ Pas} \)) with an elongated (almost) rigid particle with \( \mu_{pl} \gg 0.22 \text{ Pas} \) immersed in the fluid as a rigid phase. The particle is density neutral, both materials exhibit \( \rho = 2200 \text{ kg/m}^3 \). The geometry of the simulated box is shown in Fig. 4.2, at the beginning of computation, time \( t = 0 \), before opening the gate to let the fluid flow. The simulated particle and fluid both settle at the onset of computation, when the gate is opened. The particle orients itself with the direction of flow, as seen in Fig. 4.3 showing snapshots of simulation with OpenFOAM. This result is well in accordance with large beam tests cast with concrete where slender fibers by Dossland (2008) and crushed aggregates in large L-box castings by Halabi and Grimlund (2013) were added to the concrete mix. Evaluation after flow stoppage shows that ellipsoidal particles, fibres as well as elongated aggregates, tend to align their major axis in the direction of flow (the velocity vector \( \mathbf{u} \)). In case of radial flow, when e.g. filling a large slab by feeding the concrete at one spot in the middle and letting it flow radially, slender particles tend to orient themselves with the direction of the velocity vector. This results in an almost tangential particle lengthwise orientation in circles around the feeding
position as shown in Guideline (2013), since the tangential velocity \( u_\theta \) is more than six times larger than the radial velocity \( u_r \), \((2\pi u_r = u_\theta)\). The velocity vector \( \mathbf{u} \) is tangential to the path of moving fluid, called a streamline of the motion. In case of non-spherical particles and/or agglomerating particles, an increased viscosity due to particle motion that does not follow the streamlines can be observed. Agglomeration may be prevented by adding water reducing admixtures. Their molecules get adsorbed onto the surface of particles and increase the interparticle distance through steric hindrance and/or electrostatic effects. This decreases the magnitude of the van der Waals forces and lowers the yield stress. Since particle flocs are now broken up, the magnitude of the viscosity will be lower, however, the rotation of the non-spherical particles may still contribute to an increased viscosity. Large non-spherical particles do not affect the viscosity to the same extent, they tend to align their major axis with the velocity vector and their accumulated surface per unit volume is clearly smaller than the fine particle accumulated surface per unit volume. The shape and agglomeration tendency of small particles is an important factor influencing fluid rheology.

### 4.6 Fine Material Experiment

Cone crushed material \(< 125 \ \mu\text{m}\) was added to a cement paste mix with a volumetric concentration of 60% of the cement volume. The mix design of the cement paste is: 1000 g cement, 350 g water, 15 g superplasticizer.

The amount of superplasticizer is rather high since the suspension is designed to hold high amounts of non-spherical particles.
Figure 4.3: Four different snapshots of the simulated particle flow aligning its major axis with the flow direction, numerical simulation with OpenFOAM.
Table 4.1.
Material Data

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ [kg/m$^3$]</th>
<th>$&lt; 63\mu$m</th>
<th>Mica</th>
<th>BET m$^2$/kg</th>
<th>Aspect ratio$^\oplus$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G3</td>
<td>2650</td>
<td>8.51</td>
<td>1.5</td>
<td>873</td>
<td>3.78378</td>
</tr>
<tr>
<td>GD</td>
<td>2720</td>
<td>8.51</td>
<td></td>
<td>1045</td>
<td>2.67177</td>
</tr>
<tr>
<td>G5</td>
<td>2690</td>
<td>15.10</td>
<td>25.5</td>
<td>439</td>
<td>3.52425</td>
</tr>
<tr>
<td>G6</td>
<td>2650</td>
<td>14.19</td>
<td>22.3</td>
<td>971</td>
<td>3.11848</td>
</tr>
<tr>
<td>IL</td>
<td>2710</td>
<td>8.52</td>
<td></td>
<td>253</td>
<td>2.49874</td>
</tr>
<tr>
<td>G12</td>
<td>2710</td>
<td>11.87</td>
<td>42.5</td>
<td>954</td>
<td>4.94428</td>
</tr>
<tr>
<td>CD</td>
<td>2750</td>
<td>4.39</td>
<td></td>
<td>174</td>
<td>2.15375</td>
</tr>
</tbody>
</table>

$^\oplus$ calculation of aspect ratio as the ratio between the largest axis to the smallest axis from SEM analysis

Notation G stands for a Granite type of fine material
Notation GD stands for Granodiorite
Notation IL is an Impure Limestone
Notation CD is the abbreviation of Crystalline Dolomite

Laser sieve curve and BET surface (Brunauer-Emmett-Teller, Brunauer et al. (1938)) are carried out by Cementa AB, Sweden. The samples are all naturally dry and thoroughly mixed. Loose packing has been obtained according to NZS 3111 (1986), the material was poured into a 100 ml cylindric copper container of height 85 mm and then weighed. The cement paste rheology without the addition of fine material was measured in a MCR 300 rheometer (Physica) equipped with a concentric cylinder measuring system. The inner cylinder is profiled in order to avoid a slip surface. The plastic viscosity of the thick micro mortar fluid including 60% fine material was measured according to the channel flow method described in Chapter 3 and Paper III. The relative plastic viscosity (ratio between micro mortar viscosity and cement paste viscosity) has been plotted against the aspect ratio of the material. Fig. 4.4 shows a high correlation between aspect ratio and plastic
viscosity. For materials of equal grading curve, the correlation will be even higher, Lagerblad et al. (2013).

4.7 Result

Van der Waals forces between the finest particles create an inter-particle network that is the origin of yield stress. The fine particle mortar phase acts as a carrier of the aggregate in concrete. An increased viscosity is caused by non-spherical small particles that do not align/flow in the direction of the fluid. When applying this finding to concrete, it can be noted that a flaky particle shape (as micas) in the fine fraction should be avoided, since the increased yield stress may be compensated for. Lowering plastic viscosity, however, is not as easy. Some improvement can be made by adding small inclusions of air or silica fume (5%) or by increasing the amount of cement paste, Esping (2007).
Chapter 5

Viscosity II: Channel Flow

5.1 Summary of Finding

It has been shown that spread flow $x$ may be expressed by $x = \ell (1 - e^{-t/T})$, with $x$ a distance travelled by the fluid during time $t$, $\ell$ being the maximum spread at flow stoppage. The time constant $T$ is the amount of time it takes the fluid to travel the distance $x = 0.63 \cdot \ell$. Maximum velocity is always at the point of sudden release, at $t = 0$. Plastic viscosity may be obtained with high accuracy using just one test with the channel flow measuring device. A small material sample, a ruler and a stop watch are all it takes to make a rheological analysis with the here presented measuring procedure.

5.2 Spread Propagation

The volume mass $m$ of suspensional liquid that is suddenly released into a channel may be pictured as a build up of potential energy. Its mass is the driving force, that starts the flow. Simulations show that it actually takes a few microseconds for the potential energy to move the liquid and convert into kinetic energy. This fact is disregarded in our model, since this time frame is extremely short compared to the time of spread propagation. Releasing the flow will make it propagate and the fluid will behave like a damped wave, since the flow spreads freely and there is no additional build up of potential energy. In our long, open channel, no oscillations are to occur, implying that the system is overdamped. Its front line spreads forward according to the damping equation:

$$m\ddot{x} + c\dot{x} = 0$$

(5.1)

Once the viscous damping coefficient $c$ is determined to be $c = m/T$, the solution of this type of differential equation Kreyszig (1999) renders the spread propagation $x$ of the flowing front given by:

$$x = \ell (1 - e^{-\frac{t}{T}})$$

(5.2)
with $\ell$ being the maximum spread at flow stoppage. The spread front propagates during time $t$, the spread propagation curve shown in Fig. 5.1 is defined by final spread value and the time constant $T$, where $t = T$ at $x = \ell(1 - e^{-1})$. This means that $T$ is always the point of time at $x = 0.63\cdot \ell$. As a matter of fact, any point on the curve at $t < t_{\text{flow.stoppage}}$ together with the final spread value $x = \ell$ mathematically defines the curve. The highest speed of flow is at the point of initial release of the fluid, Alehossein et al. (2012), with $\dot{x} = \ell/T \cdot e^{-t/T}$ and $t = 0$. Boundary conditions give $\dot{x} = \ell/T$. Flow stoppage is considered to be reached at $t = 7\cdot T$, since this value

well corresponds to, or equals less than, the so called cutoff velocity of 0.03 cm/s, as stated by Tregger et al. (2008). This has been found to correspond to the times at which the human observer detects no more movement from the spread, as found by Tregger et al. (2008). For incompressible steady flow in a tube, it can be shown that for a Bingham fluid the flow rate $Q$ of the material in the pipe is described by Whorlow (1992):

$$Q = \frac{\pi \varrho^4 P}{8\eta_{pl}} - \frac{\pi \varrho^3 \tau_0}{3\eta_{pl}} + \frac{2\pi \tau_0^4}{3\eta_{pl} P^3}$$

(5.3)

with $\varrho$ denoting the radius of the tube and $P$ the pressure gradient, here equal to $\rho g$. Yield stress and plastic viscosity of the fluid are denoted $\tau_0$ and $\eta_{pl}$, respectively. Since the pressure gradient is relatively large, $P \approx 10 \cdot 2000$ Pa/m, the third term on the right hand side can be disregarded because it gives a very small contribution. It can also be shown, that for the L-box shaped geometry and rheological parameters used for the measurement in our experimental set-up, the first pressure term is considerably larger than the second term that depends on the yield stress. Disregarding the second term and taking only the first term on the right hand side into account renders the well-known Poiseuille equation, Tuchinsky (1976), from which $\eta_{pl}$ can be calculated. Thus the flow rate is inversely proportional to the viscosity. This analysis may be applied to channel flow (disregarding wall effects). The pipe radius $\varrho$ is then to be replaced with an equivalent effective radius for the box width $w$ and depth $h$. According to the concept of identical radius for two comparable fluid mechanics conduits (same area to circumference ratio,) Giles (1962), an equivalent

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Figure 5.1: Spread propagation of a fluid. Maximum velocity $\dot{x}$ occurs at the moment of release ($t = 0$): $\dot{x}_{\text{max}} = \ell/T \cdot (e^{-t/T})$. 

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36
5.3. PLASTIC VISCOSITY

effective diameter $d_L$ is:

$$d_L = 2 \frac{w \cdot h}{w + h}$$  \hspace{1cm} (5.4)

Speed of flow $\dot{x}$ is found by inserting Eq. (5.4) into the first term of Eq. (5.3) (the Poisseeuille equation):

$$\dot{x} = \frac{d_L^2 \cdot \rho \cdot g}{32 \eta_{pl}}$$  \hspace{1cm} (5.5)

5.3 Plastic Viscosity

Any point on the curve of Eq. (5.2) together with spread length $\ell$, mathematically also defines $T$. It is no longer necessary to clock the time at point $x = 0.63 \cdot \ell$. Since it is difficult to determine this exact point beforehand, a fixed point $X$ is marked in the channel where the fluid will be released. This point must not be outside the expected total flow length, but should on the other hand be located far enough from the point of release in order to obtain satisfactory clocking accuracy with the stop watch. Clocked time points ranging between a few tenths of a second up to more than ten seconds can be expected. To make different spread lengths comparable, maximum spread length $\ell$ is normalized to unit: $\ell/\ell = L_U = 1$ for all different spreads (see Fig. 5.1.) Solving for $T$, the normalized curve of Eq. (5.2) now renders:

$$T = \frac{t}{\ln \left( \frac{L_U}{L_U - x} \right)}$$  \hspace{1cm} (5.6)

Since $x = X$ is always assigned the same value and since $L_U = 1$, a linear relation exists between all $T$ and all $t_x$ values for all normalized flows. Eq. (5.6) may be rewritten as:

$$T = C \cdot t_x$$  \hspace{1cm} (5.7)

with constant $C^1$ being $C = (\ln(L_U/L_U - X))^{-1}$ and variable $t_x$ the time $t$ measured at constant distance $X$. Eq. (5.5) together with boundary conditions at the time of sudden release of flow, maximum velocity $\dot{x} = \ell/T \cdot (e^{-t/T})$, renders an expression for plastic viscosity. For the normalized expression with $L_U = 1$ it is obtained that:

$$\frac{\eta_{pl\text{, normalized}}}{\rho} = \frac{d_L^2 \cdot g \cdot C \cdot t_x}{32 L_U}$$  \hspace{1cm} (5.8)

Regarding $g, d_L$ as parameters and geometrical constants and reintroducing $\ell$ to obtain correct values for the actual flow measured, the plastic viscosity is rewritten as:

$$\frac{\eta_{pl}}{\rho_s/\rho_{water}} = A \cdot \ell \cdot t_x + B$$  \hspace{1cm} (5.9)

where parameters $A$ and $B$ incorporate $d_L, C, \rho_{water}$ and $g$ as well as frictional forces that were disregared so far.

Please note that the $C$ constant mentioned here is not equal to the $K$ constant mentioned in Paper III. This fact, however, does not affect the final result.
5.4 Practical Test Method

A practical application was developed to measure viscosity in a quick and simple way. A so-called 'Rheo-box' was constructed and calibrated against a rheometer on a small scale (micro mortar) and a viscometer in the large scale (concrete). Figure 5.2 shows the rheological measuring box, the so-called Rheo-box. It is a long channel of width \( w \). Attached, a container holding the fluid is facing the channel at one end. A set volume of fluid is filled and released into the channel when opening the gate.

![Figure 5.2: Geometry of the Rheo-box.](image)

Numerically, gate opening time is zero, since the fluid release is modelled as being instantaneous. In addition to measuring the final spread length at flow stoppage, time \( t_x \) is measured from gate opening time to the point when the concrete flow has reached a fixed travelling distance \( x \). The larger box for concrete is of 1.2 m length, the container is 0.3 m high holding a volume of 6 liters and the channel is 0.2 m wide. Time \( t_x \) is measured at a distance of \( x = 0.4 \) m from the point of release, the gate of the chimney. The small box developed for micromortar, consists of an open channel manufactured from frosted glass to ensure a low slip condition of the material. The channel is a 350 mm long horizontal open channel of 25 mm width. At one end of the channel, a \( H = 50 \) mm high gated column is attached to hold the fluid sample to be released. The chimney holds a volume of \( 19.75 \times 10^{-6} \) m\(^3\) of fluid, that can be filled into the container and then quickly released into the channel once the gate is quickly opened. Opening the container gate is performed by hand in one swift movement. Bingham parameters obtained with the Rheo-box can present complementary information of practical use for the construction site when testing concrete. On the small scale, a quick and easy paste test may determine different filler qualities at the quarry site with just small sample volumes necessary.
Chapter 6

Summary of Appended Papers

6.1 Paper I

Numerical Simulation of Fresh SCC Flow - Applications

Numerical simulation of Self-Compacting Concrete (SCC) flow shows great potential and rapid development turning into a powerful tool for prediction of SCC form filling. Numerical simulation is also of interest when it comes to modelling small scale material phenomenology. This paper presents three different applications useful for modelling different phenomena on different scales: (i) Particles, each representing an aggregate in the concrete. (ii) Fluid, modelling concrete as a homogeneous liquid and (iii) Particle in Fluid, studying details of flow. The methods are compared and evaluated in order to give the reader a quick guidance into the world of possibilities that open up with numerical simulation.

The particle and homogeneous fluid method are compared to an actual slump flow lab test. Both methods perform well, however, spread propagation of the fluid model deviates from the experimental values, as spread slows down after a correct value of $t_{500}$ was obtained. The final slump flow of the fluid model obtained at flow stoppage has proven itself to be correct. Depending on the case to be studied, the simulation method should be chosen accordingly. The fluid model gives a correct overview on a larger modeling scale whereas particle models can be employed for a higher level of detail.

This paper aims at answering research question: RQ 1: *Is is possible to simulate concrete flow?* The answer in this paper is promising and positive. However, different models are presented to simulate different aspects of the flow.

6.2 Paper II

Simulation of Fresh Concrete Channel Flow - Evaluation of Rheological parameters
CHAPTER 6. SUMMARY OF APPENDED PAPERS

The flow behaviour of fresh Self-Compacting Concrete (SCC) is investigated. This paper introduces Computational Fluid Dynamics software used here to model the flow of SCC, and its viscosity in particular. First, the simulation model is verified for a simple flow case neglecting inertia effects by comparing its final shape to a theoretical solution. Second, a new type of elongated L-box is introduced allowing measurements of speed of flow as well as spread length at flow stoppage. Finally, results based on simulations correlating flow measurements to rheological parameters are discussed and suggestions are made for the introduction of an on-site rheological evaluation technique. The flow model presented holds for the theoretical channel-flow solution on final shape at flow stoppage. Promising results indicate that the open channel flow box could produce reliable rheological parameters. These type of flow tests are not as accurate as rheological parameters produced using a rheometer in the lab environment. However, they could present complementary information for the construction site.

This paper focuses on research question RQ 2: Is it possible to obtain a value for plastic viscosity other than in a viscometer? Concrete open channel flow seems to be one answer to this question.

6.3 Paper III

Obtaining Rheological Parameters from Flow Test - Analytical, Computational and Lab Test Approach

In the mix design process of cementitious suspensions, an adequate rheology of the cement paste is crucial. A novel rheological field test device for cementitious fluids is presented here and investigated theoretically, numerically and by lab tests. It has been shown that spread flow $x$ may be expressed by $x = \ell(1 - e^{-t/T})$, with $x$ a distance travelled by the fluid during time $t$, $\ell$ being the maximum spread at flow stoppage. The time constant $T$ is the time span from the fluid release until the fluid passes the distance $x = 0.63 \cdot \ell$. Maximum velocity is always at the point of sudden release. Plastic viscosity may be obtained with high accuracy using just one test with the channel flow measuring device. A small material sample, a ruler and a stop watch are all it takes for a rheological analysis with the here presented measuring procedure. A quick and simple paste test to determine different filler qualitities at the quarry site is now possible with just small sample volumes available. The results presented here correlate key values of open channel flow to rheological Bingham parameters. This novel rheological test method also enables the correlation of different rheological equipment used by different laboratories.

This paper also concerns research question RQ 2: Is it possible to obtain a value for plastic viscosity other than in a viscometer? The study in this paper is on a small scale: micromortars. An analytical solution presented shows the relation between open channel flow parameters and the plastic viscosity.
6.4 Paper IV

Evaluation of Crushed Fine Materials

This paper is the implementation of the method presented in Paper III, different types of fine material are investigated. In the mix design process of cementitious suspensions, an adequate rheology of the micro mortar (all constituents in the concrete being able to pass a 0.125 mm sieve, including the cement) is crucial. In this paper, the shape of fine particles is linked to the micro mortar plastic viscosity of the filler suspension including cement. The plastic viscosity here serves as an important quality assessment of the filler, since the micro mortar workability features are vital for the final mix design quality of the concrete workability. This shows, that one simple mix of paste is sufficient to determine the quality of the fine material, such as aspect ratio and suitability for concrete mix design. Loose packing may also give an indication of mica content, which affects aspect ratio to a great extent. A clear correlation between mica content and an unfavourable particle shape of the fine material has been established. However, an easy-to-use quick rheological micro mortar test will provide an adequate quality assessment of the tested filler added to the cement paste. A testing volume as small as $19.75 \cdot 10^{-6} \text{ m}^3$ fluid is sufficient to obtain this important information about the filler quality.

The study of particle shape in this paper is linked to research question RQ 3: *Is there a simple way to determine particle shape?* As shown in the paper, particle shape may be determined by loose packing methods to an adequate accuracy for a fine $63 - 125 \text{ } \mu \text{m}$ material.

6.5 Paper V

Particle Motion in Fluid - Analytical and Numerical Study

This paper focuses on the motion of differently sized particles in fluid, from the microscale to the macroscale with no more than one particle in the fluid up to dense particle systems, such as cementitious suspensions. Also, it was shown by numerical simulation that an elongated particle will align its major axis with the flow direction. The centre of the particle follows the fluid flow along the streamlines. Finer particles may rotate between the larger particles moving at different velocities or once the streamlined flow is not linear, as in corners and bends. The rotation of crushed, non-spherical finer particles as well as particles of a few microns that agglomerate leads to an increased viscosity of the fluid. Another factor of non-spherical fines increasing the viscosity of a suspension is the larger particle surface area to be wetted by fluid compared to the surface area of a sphere. This effect densifies the particle system and increases flocculation. Flocs may be broken by superplasticisers, however the particular rotation of non-spherical particles will still increase viscosity. In addition to this, the amount of fine particles by far exceed the amount of larger particles in a normal or self-compacting concrete. This makes the fine particle shape even more
important determining the rheological properties of a suspension.

The content of this paper answers research question RQ 4: How do particles behave during fluid flow and in what way does this behaviour affect suspensional viscosity?
Chapter 7

Discussion

Cementitious fluids consist of a wide range of particle sizes. It is a suspension of particles that may differ a factor by $10^7$ in size. Naturally, these particles exhibit different types of behaviour according to their physical and chemical features.

Particles in the microscale are subjected to hydrodynamic forces as well as Brownian motion and colloidal forces created by van der Waals attraction and electrostatic repulsion. The qualities of the microscale are to a large extent dependent on these forces, which need to be taken into account when modelling the microscale.

Modelling on the mesoscale includes taking into account the impact of particles surrounded by fluid. It is intended to bridge the gap between microscale and macroscale and is a research field of constant development.

On the macroscale, however, just one homogeneous fluid is perceptible. This gives us the overall picture of the fluid. It is worth noting, however, that even for homogeneous deformation on the macroscopic scale, at the atomic level this deformation is highly inhomogeneous. A macroscopic model from an atomic perspective is not realistic with desktop computer power available to date.

The models presented in this dissertation are in the mesoscale including the particles and macroscale (CFD homogenous approach).

As for the different scalings, there is no straightforward way to transpose the scales, they are model independent from one another. When it comes to sample size and the objects included in it, sufficient care must be taken to model a volume large enough to be representative for the particles included and the scale that it represents.

The same holds true for the amount of particles when simulating with DEM. An insufficient amount of particles will influence the slump flow behaviour for example. However, computer systems available today put an absolute limit on the amount of particles used in PFC to no more than one million.

To save computation time and reducing the number of particles, a mortar layered aggregate particle was introduced, with a soft coating hiding a hard kernel, Gram (2009). This model allows for larger volumes of non-segregating SCC to be simu-
lated. However, it is not suitable to simulate aggregate jamming or segregation of
the concrete. The roundness and slippery surface of the mortar coating prevents
any particles from forming a granular arch behind the rebars.

Separate mortar and aggregate particles would allow for e.g. blocking to be mod-
elled. Perfectly rounded particles with little or no friction may show blocking be-
haviour (see Fig. 7.1), but do rarely (if at all) form granular arches, which is why
particle shape and friction (surface roughness) are important parameters, just as the
maximum particle size, particle concentration and sieve curve distribution.

Figure 7.1: DEM particle simulation showing the height difference of the concrete
before and after passing the rebars. Shown to the right is blocking behav-
ior with clear granular arches between each bar.

A simplistic particle model in the microscale was introduced in Chapter 4 and Paper
V, explaining how particle flocculation may increase yield stress and plastic viscosity.
The rotation of small spheroids increases the level of viscosity, which is not simulated
here. A different type of customized CFD solver would be required with more user
modifications in order to simulate particles exhibiting colloidal forces. It is very rare
to simulate particle flow at this scale of observation. One single particle is simulated
in the mesoscale with the software femLego as a falling particle. A flowing particle
aligning itself in the flow direction was numerically modelled with CFD software
OpenFOAM.

Different computer models have been developed in order to study different phe-
nomena. The different methods have performed well within their range of model.
Detailing end phenomenology can be captured with a particle approach, an overall
picture of the flow is well given by the fluid approach. As stated by Geiker et al.
(2005), homogenous fluid simulations combined with particle flow approach specified
for details in constrained areas will provide an optimal tool at low computational
costs.
Chapter 8

Conclusions and Further Research

Four research questions were posed in the Introduction that have been answered:

RQ 1: *Is it possible to simulate concrete flow?*
RQ 2: *Is it possible to obtain a value for plastic viscosity other than in a viscometer?*
RQ 3: *Is there a simple way to determine particle shape?*
RQ 4: *How do particles behave during fluid flow and in what way does this behaviour affect suspensional viscosity?*

The original assumption that it would be possible to numerically simulate the flow of Self-Compacting Concrete (SCC) still holds. A conclusion that can be drawn is the importance of scaling and choice of method when selecting a model, RQ 1.

The objective of this thesis, to gain an increased understanding of how aggregate properties influence fresh concrete rheology, especially the viscosity, has been studied experimentally, analytically and numerically. It can be concluded that mostly the fine particle fraction contributes to an increased viscosity. The original hypothesis, that the rotation and movement of elliptical particles require more paste and therefore increase Bingham parameters, can now be modified.

Larger, non-spherical particles align their major axis with the flow direction, their contribution to an increased workability during flow is small to none. It was found however, that small particles may rotate between larger particles, even during laminar flow. The fact that particles move in a direction different from the flow velocity increases the viscosity of the fluid, RQ 4.

A simple way to obtain plastic viscosity was obtained by studying parameters from open channel flow, RQ 2. This way, Bingham parameters can easily be found on-site for concrete and for micro mortar as a simple filler acceptance test in the quarry. For fine material, 63 – 125 µm, this acceptance test on particle shape may also be done with a method of loose packing of aggregates, RQ 3.

This answers the research questions posed in the Introduction.
For the future:

There is still to come a universal material model that fully covers all the phenomena that play an important role during flow and casting of SCC. Different simulation models are good for explaining and predicting different phenomena.

SCC test methods (e.g. slump flow, J-ring) were performed and recorded in the laboratory before the simulation.

A particle approach (DEM) will be able to explain phenomenology of forces acting on spherical or non-spherical aggregates during mixing, packing or flowing. DEM also allows a qualitatively correct simulation of blocking and the formation of granular arches in congested areas, given particle shape and friction are included in the model. This method is most adequate in the study of details and phenomenology.

It would be interesting to further explore details of agglomeration and non-spherical particle rotation in the colloidal range using DEM in order to further explore dispersion effects of different superplasticizers.

An in-depth study of loose particle packing including larger aggregates of different aspect ratios and friction coefficients (surface texture) would further clarify the influence of parameters such as wall effects, surface texture, grading and aspect ratio on values of Random Loose Packing (RLP). Concrete mixes of optimal RLP could be produced to measure and compare rheological values.

A homogeneous approach (CFD) is more computer efficient. It may serve to model large volumes of concrete flow as well as incomplete form filling (however, no segregation or forming of granular arches) due to poor compatibility between the geometry of the formwork and the rheology of the concrete. It may well serve as a powerful tool to guide the pre-selection of formwork and rheological parameters of the concrete for an optimized match.

CFD may be employed for a large scale simulation to obtain an overview on possible problem areas, which could then readily be modeled in detail with DEM. An easy accessible toolkit to use before casting and as feedback for quality control of the concrete delivered to the work site is a long term goal.

A novel OpenFOAM solver for CFD with hard, non-spherical inclusions cross-linked to influence the fluid viscosity could further explain the phenomenology of small rotating particles.

As computer speed and capacity develop, merging the two described approaches, particle and fluid, will form a new dimension in simulation of suspension flow. This is most likely the path taken in the future. A simple case of one single particle in fluid was studied here as a first small step.
References


REFERENCES


Fuller, W. B., Thompson, S. E., 1907. The laws of proportioning concrete. Transactions of the American Society of Civil Engineers 33, 222–298.


Appendix A

Appended papers