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Performance based concrete mix-design

Aggregate and micro mortar optimization applied on self-compacting concrete containing fly ash

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Acti labores jucundi

PREFACE

Working with a doctoral thesis can be likening to a road trip by car. You can choose the straight high-speed freeway and arrive to your destination quick and easy, or you can choose the small curved way, which probably will take longer time. There are advantages with each alternative; the freeway will be a short trip and you will save time, but you will probably miss the surroundings passing by outside the car window. The small curved way might delay you, but on the other hand, you will be able to experience the landscape outside.

For some reasons, my doctoral education became the curved way of driving on my journey. It took some time, but I have experienced and learned a lot. As a co-driver at my journey I have had the privilege in having Professor Jan-Erik Jonasson by my side. He has been my supervisor during the years and I am extremely grateful for his guidance, support and never ever ceasing optimism, even through times when my own doubts have been high. This thesis should never been written without you Jan-Erik!

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The work presented in this thesis has been carried out at the Division of Structural Engineering and to my colleagues I would like to say; Thank You All for a very pleasant time! I will send a special thanks to Professor Thomas Olofsson, Professor Mats Emborg, Associated professor Lars Bernspång and Ph.D. Martin Nilsson.
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To my parents Ulla and Svante and my parents in law Carin and Lars; I hope you all know how priceless your help with our children is!

The last weeks when writing a doctoral thesis can be, to say the least, very intensive. It is a period when the person you spend most of the time with is your supervisor. When having two children, a house and a huge pile of laundry at home, things might be shaping up for chaos. To Fredrik, my husband, friend and mainstay; There are not words enough to express how grateful I am that you have been taken care of everything at home the last weeks when I have been working or been totally lost in thoughts.
To Hjalmar and Oskar, my sunshine; Mum's book is finally completed and I promise you that we will go to Leos Lekland! Conclusion: Anything is possible with these three guys by my side. I love You!

Finally, I can stop the engine of my car, I have reached my destination and this journey has come to an end!

Luleå in the middle of October 2008

Sofia Utsi

ABSTRACT

This thesis is dealing with the field of self-compacting concrete (SCC). SCC is supposed to fill the form properly and enclose the reinforcement without any external vibration. The fresh properties of such a concrete are thus essential. SCC was first introduced in Japan in the middle of 1980^{th}. Due to the high demands on its fresh properties, the mix-design process is more complex for SCC than for normal vibrated concrete and generally, it has higher content of powder materials, such as cement and mineral additives.

In this thesis, a performance based mix-design method is proposed. Performance based means that concrete shall be composed regarding the properties of available materials and due to the properties of the element to be cast. The main objective with performance based concrete mix-design is to utilize the properties of the available materials to increase the cost-effectiveness in concrete production.

The main part of the thesis has been to propose how available materials can be combined, due to their specific properties, for further use in concrete. The material selection shall, in addition to the material related properties, be based on the performance of the structural element to be cast. In the thesis, a method to choose an appropriate micro mortar is presented as well as how an appropriate aggregate grading curve can be combined based on material related properties. To fully utilize the potential of the suggested method, a connection parameter between micro mortar and aggregates is introduced. A structured method for how decisions can be made, based on results from micro mortar tests and aggregate optimization tests, to compose a SCC mix that is appropriate for its specific field of application is suggested.

SCC has a relatively high content of powder materials. In addition to cement, limestone filler or fly ash is often used. Fly ash is an industrial by-product from coal-fired power stations and it has been proven to be a sufficient concrete making material when replacing cement in varying amounts. Swedish concrete producers do not have a tradition in using fly ash in any wider extension because of the lack of nationally produced fly ashes. However, there is an increasing interest to use more fly ash as filler material in concrete in Sweden. Fly ash is a pozzolnaic material, which means that it will influence the young and hardened properties.

This thesis contains an investigation of the effect of fly ash on the hardening properties. A numerical prediction model for heat development and strength growth is presented. The prediction model will for instance facilitate the possibility to calculate appropriate form removal times for concrete with different water to powder ratios containing varying amounts of fly ash.

In addition, the risk for early thermal cracking of concrete containing fly ash in varying amounts has been investigated. It was concluded that mixes containing fly ash and limestone filler have an increased early-age creep. It was also concluded from a numeri-

cal stress analysis that the risk for early age through cracks is significantly decreased for mixes containing fly ash. The estimated risk for surface cracks was not improved by an incorporation of fly ash. The estimated risk for surface cracks for concrete containing limestone filler was significantly lower in comparison to the other tested mixes, i.e. Portland cement concrete and concrete containing fly ash, which might be a combined effect from moderate heat development and increased early-age creep.

SAMMANFATTNING

Självkompakterande betong (SKB) skall fylla formen och omsluta armeringen utan yttre vibrering. SKB introducerades i mitten av 1980-talet och Japan var pionjärer inom området. För att SKB skall kunna flyta ut ordentligt utan att ballasten separerar så ställs det höga krav på den färska betongen. Den största skillnaden mellan SKB och normalvibrerad betong nämns ofta som lägre vatten pulver tal, större andel cementpasta, lägre andel grovballast samt inblandning av effektiva superplastiserare. Mycket forskning har bedrivits inom området sedan SKB introducerades för första gången, och flertalet proportionerings metoder har utvecklats genom åren.

I den här avhandlingen ges ett förslag på hur man kan välja tillgängligt material på bästa möjliga sätt så att det passar det tänkta tillämpningsområdet, s.k. utförandebaserad optimering. Syftet med utförandebaserad optimering är att tillvarata egenskaperna från det tillgängliga materialet på bästa möjliga sätt.

Metodiken bygger på enkla verktyg för att karakterisera egenskaper som är av vikt för den färska betongblandingen. En metodik för finbruksoptimering tillsammans med en metod för hur man kan välja en lämplig graderingskurva föreslås. Resultaten från dessa två kopplas sedan samman med en föreslagen kopplingsparameter, vilken möjliggör en direkt översättning mellan finbruksfasen och den valda graderingen. En strukturerad metod föreslås för hur delmaterialen kan sättas samman utifrån tillämpningsområdet samt hur justeringar kan göras för att förändra de färska egenskaperna.

Självkompakterande betong innehåller en relativt hög andel finpulvrigt material, tex. kalkstensfiller, silika eller flygaska. Flygaska är en mineralprodukt som uppstår vid koleldning vid el- och värmeproduktion. Flygaskans sfäriska och släta partiklar i kombination med dess låga densitet har visat sig ha fördelaktiga egenskaper i den färska betongen. Flygaska har inte varit särskilt vanligt vid svensk betongtillverkning, främst på grund liten inhemsk produktion av högkvalitativ flygaska. Intresset för flygaska har dock ökat under de senaste åren. Då flygaska har pozzolana egenskaper så kommer dess inblandning i betong att påverka de unga och mogna egenskaperna.

Den här avhandlingen inkluderar en undersökning av flygaskans inverkan på egenskaperna i den unga betongen. En numerisk tendensmodell är etablerad, vilken gör det möjligt att prediktera värme- och hållfasthetsutveckling i en betong innehållande flygaska i varierande mängd samt för varierande vattencementtal. Det möjliggör beräkningar av t.ex. formrivningstid eller åtgärder för att förhindra tidig frysning då flygaska används.

Risken för tidiga temperatursprickor hos betong innehållande flygaska har även testats. Resultaten visar att risken för genomgående sprickor minskar signifikant för betong innehållande flygaska i jämförelse med betong tillverkad av endast Portland cement. Risken för tidiga ytsprickor blir dock inte förbättrad med inblandning av flygaska.

NOTATIONS AND SYMBOLS

B=binder content,

$B=C+FA+SF+Sl$

C=cement content, kg/m^3

$Cequ$=equivalent cement content, kg/m^3

$Cequ=C+k_{FA}FA+k_{SF}SF+k_{Sl}Sl$

Coarse aggregate= >4mm

FA=fly ash content, kg/m^3

Fi=non reactive mineral additives, kg/m^3

Fine aggregate= 0-4mm

HWRA=High water reducing agent

P=powder content, kg/m^3

P= C+FA+SF+Sl+Fi

SF=silica fume content, kg/m^3

Sl=slag content, kg/m^3

w_0=mixing water content, kg/m^3

w_0/C=water-to-cement ratio, w/c-ratio

w_0/C_{equ}=Equivalent water-to-cement ratio

w_0/P=water to powder ratio

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1 INTRODUCTION

1.1 Introduction to self-compacting concrete

Self-compacting concrete (SCC) is a concrete mix that in its fresh phase, homogenously flows by its own weight, and fills out the formwork properly and encloses the reinforcement without any external vibration. It was in the middle of 1980th that self-compacting concrete first was developed and introduced at Tokyo University. Japan had experiences from several durability problems in construction where the quality of the concrete was not as good as expected and in the beginning of 1983 problems were viewed as a major problem facing these constructions. The introduction of SCC was proposed as a new concept to build more durable and reliable concrete structures. The main reasons for the lack of quality were a reduced number of skilled workers, and it was suggested that "vibration-free concrete" might be the solution for their problems because it facilitated remained productivity to a limited number of skilled workers needed (Okamura and Ozawa 1995, Okamura and Ozawa 1996, Okamura 1997, Ouchi 1998, Okamura and Ozawa 1999).

The most important advantages with SCC are often mentioned as the following:

- Reduce labour resources
- Increased productivity
- Eliminate noise and "white fingers" associated with vibrating, which will improve the work environment for the workers.
- More innovative construction systems

The concrete properties at early and at a hardened stage are expected to be almost similar as for normal vibrated concrete. The biggest difference between normal vibrated concrete (NC) and SCC can be addressed to the fresh phase comprising very high demands on its fresh properties; high homogenous flowability without segregation or blocking of the coarse aggregate (Okamura and Ozawa, 1996, Yurugi et al. 1996, Okamura 1997, Takada et al. 1998, Noguchi and Mori, 1998).

The development of SCC in Sweden started in 1993 when CBI, the Swedish Cement and Concrete Institute, arranged a seminar about SCC with contractors and producers invited. The main purpose with the seminar was to find collaboration partners to develop SCC in Sweden. This lead to a project financed by NCC, Betongindustri and the Swedish Work Environment Fund. The project presented a literature review and performed basic research in laboratory where different fillers were investigated and the blocking criteria for crushed aggregate were developed. A large number of half scale house-walls using different filler materials were also cast within the project, see Petersson et al. (1996a) and Billberg (1999a).

In 1998 the first full-scale bridge was cast with SCC, initiated by the Swedish Road Administrator (Petersson et al. 1998a and Nilsson 1998)

In 1997 a Brite-Euram project started, entitled "Rational production and improved working environment through using self-compacting concrete". The project has been carried out by several partners e.g. research institutes, universities, contractors and material producers from five European countries. The research formed the base for starting several pilot full scale constructions with SCC. Thus, a large amount of bridges, tunnel linings, walls and slabs of houses and many types of prefabricated elements have been cast with self-compacting concrete, see e.g. Grauers (1999).

1.2 Identification of the problem

1.2.1 SCC mix-design

Due to the high fresh property requirements, a proper mix-design method is essential to succeed using self-compacting concrete. Concrete mix-design means a method to choose the constituents in different amounts to achieve a concrete mix with sufficient properties appropriate for the current application. The mix shall fulfill stated demands in fresh, young and hardened phase. The first SCC mix-design method that was introduced can be addressed to the "Japanese method". During the years, since the middle of the eighties, a lot of research has been performed to refine the mix-design process for SCC and a large number of design methods for SCC have been proposed.

Nowadays, self-compacting concrete is used regularly in full production as an alternative to normal vibrated concrete. A SCC mix can be produced with locally available ordinary concrete making materials and the general standard method is known as; increase the filler content, decrease the coarse aggregate content and add a high water reducing agent (HWRA).

The difficulty with production of SCC is to succeed with the concrete within reasonable economical frames and to reach repeatable properties trough the whole production chain, i.e. sufficient robustness. The material costs for SCC is in general higher than ordinary vibrated concrete because of the increased amount of cementious materials, fillers and third generation of superplastiziser. In addition, using SCC is often associated with a large number of preliminary examinations and an extensive quality control work during the production to ensure the established conditions. Many contractors do not see a clear benefit in choosing SCC as an alternative. To reach higher acceptance among contractors, self-compacting concrete must be a competitive alternative to normal vibrated concrete, and cost-effectiveness is an important aspect. Cost-effective means a concrete mix that show high reliability, lean resource utilization, i.e. materials are chosen to make the best use out of them, and also suited for its specific type of application.

It is often argued that SCC is more sensitive regarding the external conditions and the material used. Skarendahl (2003) emphasis that mix-design and performance parameters for SCC are, in a larger extension than for normal vibrated concrete, dependent on the properties of the available materials. A direct comparison between different SCC mixes shall only be done with caution, because SCC is more sensitive against outer disturbance in general.

Domone (2006a) reviewed 68 case studies performed with SCC, regarding the distribution of the constituents and its corresponding workability. He found that the constituents and the mix proportions were spread in a relatively wide range, but still, each case study were successfully performed. This indicates that a well working SCC can be produced in a lot of different ways with various proportions between the constituents and that no unique standard rule exists, and Domone discussed that SCC comprises a wide range of mixes. Further, he concluded that there is a potential in optimizing SCC with higher efficiency, which can be reached when type of application and the properties from locally available materials are taken into consideration in a larger extent.

1.2.2 Using fly ash in concrete

Self-compacting concrete contains relatively high content of powder materials, which includes cement and some type of mineral additive. Fly ash can preferably be used in concrete, either as replacement of some of the cement content or as replacement of parts of the aggregate, i.e. an extra filler material. Fly ash is an industrial by-product from coal-fired power stations and it has been proven to be a sufficient concrete making material when replacing cement in varying amounts. It comprises spherical glassy particles in the size of cement, approximately 1 to 150 μm. The spherical shape has been proven to improve the workability of fresh concrete and the water content needed for a certain workability can be reduced (Davis et al., 1937, Berry and Malhotra, 1980, Lane and Best., 1982, Bilodeau and Malhotra, 2000).

Fly ash is a pozzolanic material, which means that it reacts with the calcium hydroxide $Ca(OH)_2$ that is produced when cement reacts with water. When fly ash reacts with $Ca(OH)_2$, calcium silicate hydrate (CSH) is formed, the content of the durable material (CSH) will thus increase in the concrete(Papadakis et al., 1992 and Fraay et al., 1989). Fly ash is often used in concrete because of its excellent concrete making properties, especially in the fresh phase. Any incorporation of a pozzolanic material in concrete will influence the young and hardened concrete properties. It is thus essential to understand how concrete properties will be influenced when fly ash is added to ensure the concrete performance.

Fly ash in concrete is not common in Swedish concrete production, mainly because of the lack of national produced fly ash. However, there is an increased interest among concrete producers to use fly ash in concrete, either to replace some of the cement content or to replace parts of the aggregate in SCC. The effect of fly ash on concrete properties when combined with Swedish cement is thus important to document to ensure the concrete performance for fresh, hardening and mature concrete.

1.3 Possible approach to a solution

1.3.1 SCC mix-design

One large challenge within the SCC production nowadays is to increase the possibility to produce a more cost-effective material. A structured method that facilitates the possibility to compose the available constituents in appropriate proportions tailored for the actual type of application, stated criteria and the external conditions is thus needed.

The properties of fresh concrete is a complicated interplay between numerous of factors, which all together shall be taken into consideration during the mix-design process. All factors are important by themselves and when mixed together, they will form a concrete composition. It includes a comprehensive perspective from the smallest particles to the total concrete composite.

A possible approach to a solution has, in this thesis, been to investigate how available materials can be combined, due to their specific properties, for further use in concrete. The material selection has, in addition to the material related properties, been based on the performance of the structural element to be cast. It is based on a comprehensive and practical oriented mix-design method that is easy to perform in a non complicated way, but still receives adequate material characterizations. The aim of the method is that the effect from different amounts and types of materials on the fresh concrete properties should be easy to evaluate for decisions regarding the actual application where cost versus benefit should be able to consider.

1.3.2 Using fly ash in concrete

Incorporation of fly ash will, among other things, influence both the heat of hydration and the strength growth. In some cases a decreased heat of hydration can be favorable for the structure, e.g. in massive constructions. In other cases, e.g. winter casting, the reduced or delayed heat development can cause serious problems. Fly ash in concrete shall thus be used with caution, and possible problems for the structure should be analyzed. The most commonly mentioned effects of fly ash in concrete are; reduced heat development and strength growth. These two properties are essential for the young concrete behaviour and will influence form removal times, the time needed for moisture curing and the risk for early freezing. Tools for estimating the effect from fly ash in varying amounts of the young concrete behaviour will facilitate the possibility to use fly ash in concrete without jeopardize the concrete performance.

1.4 Performance based concrete mix-design

Performance based concrete mix-design for normal vibrated concrete was discussed by Shilstone et al. (1999) and Shilstone SR and Shilstone JR (2002). The authors were discussing that existing codes and standards might be conservative in some cases because they mostly are based on strength requirements. For some cases, strength may not be the most important criteria and concrete composed due to standards and codes can be unnecessary expensive and inefficient. The main objective with the idea with performance based concrete mix-design is to facilitate the possibility to design tailor made concrete mixes regarding locally available materials, functional demands and type of application, which can increase the possibility to design safer, more reliable and cost effective concrete mixes. Shilstone et al. (1999) were defining performance based as: *"Specifications and/or methods that will contribute to production of the desired levels of engineering, construction, and durability properties required for economy and long-term serviceability of the concrete project"*.

1.5 Aim and scope of work

There are two main objectives with the work performed within this thesis:

1. *To develop a systematic mix-design method for self-compacting concrete that will facilitate a performance based perspective on concrete mix-design.*

Performance based mix-design is a big area with numerous possible types of material, field of applications and related demands. However, with reliable mix-design tools, the possibility to choose appropriate combination of materials might increase. The main objective with the work performed in this thesis is to develop an experimentally based mix-design method for self-compacting concrete, the λ_{25} mix-design method, which is expected to be a useful tool when applying a performance based perspective. Focus is held on material related properties and how to compose the constituents regarding the structure to be cast. The context for the performed work is how to combine available materials to receive, for the actual structural element, the most appropriate SCC mix.

In the performed work, concrete is regarded as solid particles suspended in water where the finest particles can, experimentally, be regarded as micro mortar. The micro mortar and the aggregate are composed separately and connected to a concrete mix. The connection part is essential, since decisions taken in each phase shall be reflected in the concrete matrix.

The main objective with the work regarding the micro mortar approach is to develop a systematic method for practical micro mortar optimization with the aim to evaluate how available materials can be combined to receive appropriate fluidity and robustness for the actual field of application. It is performed in a manner that makes it possible to compose a micro mortar that is direct related to the actual aggregate grading curve.

Regarding the aggregate, the thesis comprises an investigation of how an aggregate grading curve can be composed regarding its specific properties and due to the structural performance. A systematic way of working with aggregate with the aim to choose an appropriate grading curve for self-compacting concrete is proposed.

2. *Evaluate the effect of fly ash on the properties in the young concrete*

The main objective with the performed work regarding fly ash in concrete has been to evaluate the effect of fly ash on the young concrete properties and its effect on; heat development, strength growth and the risk for early thermal cracking.

A numerical tendency model for the heat of hydration and the strength growth is established. It makes it possible to predict strength growth and heat development for different water-to-cement ratios with different fly ash contents. It will increase the potential of using fly ash for different types of applications when important properties such as heat and strength development can be predicted.

For example, for civil engineering applications, reducing the early thermal cracking is essential for the structure. Cracks can cause serious damage and durability problems in the future. It is thus essential to understand how the incorporation of fly ash will affect early age properties of concrete. In the work, the risk for early thermal cracking in concrete is tested and evaluated for SCC containing fly ash as a partial replacement of the aggregate.

1.6 Limitations

This thesis is oriented in a wide field of research area, where each part of it is very interesting to look more thoroughly into. To avoid a never ending story in this thesis, some main limitations have been performed.

Some of the limitations are valid for both the mix-design development and the fly ash investigations. The work presented in this thesis is limited to self-compacting concrete aimed for civil engineering applications. It means that it only comprises concrete containing cement of the type Anläggningscement Std P Degerhamn CEM I 42.5 N BV/SR/LA, produced by Cementa AB. Tests have also been performed with only one type of superplastiziser, Sikament 56, produced by Sika AB.

Regarding the mix-design development, the following limitations have been made:

- Performance based concrete mix-design includes the properties from fresh to mature concrete. It can include demands on strength, durability, surface smoothness or limitation of early cracks. These areas can be formulated as stated demands which are important to fulfill. This thesis is limited to fresh concrete properties, which only includes a mix-design method that will facilitate the possibility to compose SCC with a performance based perspective. The method do not consider how SCC shall be composed regarding demands on young and mature concrete.
- SCC mix-design involves fundamental understanding of the effect from different parameters involved in the concrete mix. The work performed within the frame of this thesis is based on the composite mechanisms in concrete mix-design rather than the effect of single parameters.

Regarding the fly ash investigations, there are also some limitations performed.

- Firstly, only one type of fly ash has been tested. It shall be noted that the variation in properties between different types of ashes, even if they are suited for concrete, can be relatively high and the properties is depended on the chemical composition and the grain size, shape and distribution for each fly ash. These variations will of course affect the concrete properties, it shall thus be mentioned that the results from one fly ash can not directly be translated to any other type of fly ash.
- Secondly, fly ash is evaluated regarding its effect on some predetermined important concrete properties. As this thesis deals with concrete aimed for civil engineering ap-

plications, the following properties have been examined: strength- and heat development and the risk for early thermal cracking.

- The very important aspects on durability when using fly ash are not included in this thesis.
- All modelling for description of properties using fly ash is based on experimental results, and no effort is made to derive phenomena based on fundamental knowledge concerning chemistry and physics, e.g. the effect from pozzolanic reaction. However, some empirical models are based on well-known material related parameters.

1.7 Outline of the thesis

Chapter 2 is presenting a review of literature regarding SCC with focus held on mix-design and fresh properties.

Chapter 3 presents the suggested mix-design method, which is based on the results from paper A and paper B.

Chapter 4 contains a summary of appended papers C and D. The most important results are summarized and discussed.

Chapter 5 involves a summary and conclusions.

Chapter 6 presents some suggestions to future work.

Four papers are appended to this thesis:

Paper A: "A performance based experimental micro mortar optimization method for SCC" Aimed to be published in: Cement & Concrete Research

Paper B: "A method for practical aggregate optimization aimed for self-compacting concrete mix-design" Aimed to be published in: Cement & Concrete Research

Paper C: "Heat and strength development for concrete containing Fly ash" Aimed to be published in: Nordic Concrete Research

Paper D: "Estimation of the risk for early thermal cracking for SCC containing Fly ash" Aimed to be published in: Materials and Structures

2 SELF-COMPACTING CONCRETE MIX-DESIGN

2.1 Introduction to SCC

SCC shall flow by its own weight, fill the formwork and enclose the reinforcement without any external vibration. This involves high deformability of the paste and also resistance to segregation between the coarse aggregate and the mortar. However, it is not possible to achieve this high deformability by only increasing the water content, but when the third generation of superplastiziser entered the market, it became possible. To increase the viscosity of the mortar and thereby increase the resistance to segregation, cement and other fine materials, e.g. limestone filler and fly ash, are needed in larger proportions than in conventional concrete to obtain the desired cohesion (Hurd, 2002). Self-compacting concrete contains cement, mineral additives, e.g. limestone filler, fly ash or silica fume, aggregate and a high water reducing agent (HWRA). According to an investigation performed by Domone (2006a), the powder content in SCC normally ranges from 425 to 625 kg/m^3. Moreover, aggregate for normal concrete is in general suitable for SCC, but according to Hurd (2002) the grading will probably be different.

A numerous mix-design approaches for SCC have been suggested in literature; both experimental based methods and computer based models. Some general rules to succeed with SCC in comparison with conventional concrete can be summarized; lower water/powder ratio, higher paste content, limited coarse aggregate content, adding superplastisizer and in some cases using a viscosity modifying admixture.

2.2 Fundamental theories of concrete workability

For better understanding about the complexity on how to compose a fresh self-compacting concrete, it is an advantage to start with the basic theory of ordinary concrete workability.

An unworkable concrete is a mix with solid particles locked together forming a rigid structure. A workable concrete, on the other hand, is a mix where solid particles are suspended in water. As an alternative, workable concrete can be seen as cement and mineral additives suspended in water forming the paste, and aggregate suspended in the paste. The workability of fresh ordinary concrete can be addressed to a complicated interaction between the available materials regarding type, size and quantity. According to Powers (1932), the workability of normal vibrated concrete is, above all, determined by the combined effects of three factors:

1) The quantity of the cement paste, in relation to the concrete volume

2) The consistency of the paste, depending on the proportions and properties of the available materials.
3) The gradation and type of the aggregate.

Powers also summarizes some conclusions regarding the effect of each factor as follows:

The consistency of paste: The factors influencing the workability of paste are mainly a function of the amount of solid particles, in a given volume of water, and the fineness of the particles. In cases with higher content of particles in a given volume of water, the rate of flow will decrease. This is a consequence from that the particles are less free to move for two reasons; 1) the total surface area is increased, which increases the total force of surface tension and 2) the particles are compacted closer together. The opposite, reducing the solid particles in water, will reduce the total force of surface tension and increase the freedom to move for each individual particle.

The consistency of the paste and its relation to the workability of concrete is also a function of the gradation of the aggregate. For coarser gradations, an increase in the paste workability can result in a decrease of the concrete workability. Powers concludes that for a given paste content combined with some gradation, there is an optimum paste consistency to reach an optimum workability.

The paste content: For a fixed aggregate gradation, the workability of a concrete mix will increase with increased paste content. This can be compared to the workability of cement paste; when the solid particles are further suspended in water, the workability increases. When the suspension of aggregates in paste increases, the concrete workability will increase. At low paste content, the surface tension per unit volume is greater and in addition, the particles are crowded closer together. This will result in a stiffer and less workable concrete mix. However, increasing the paste in order to improve the workability is only favorable to a certain degree. Over a given paste content limit, the particles will not be further suspended and a paste content increase will not further increase the workability.

The effect of sand content: Powers (1932) also describes the effect of the sand content in concrete and its corresponding workability. By increasing the sand content, in percent of the total aggregate content, the workability will be reduced for a given paste content. For each water-to-cement ratio, coarse aggregate gradation and expected workability, there is an optimal percentage of sand which requires the least quantity of paste. Generally, for a given workability, higher sand contents require more paste than lower contents of sand, i.e. sand content is strongly related to both paste content and its water-to-powder ratio.

However, very low sand contents, which will result in higher coarse aggregate content, require higher paste contents, which is described by the effect of the particles size in comparison to the distance between them. When the particle size becomes great in comparison to the distance between them, as in the case with low sand content, the particle interference will play an important role and the paste content must thus be increased to receive sufficient workability.

In addition to the pure sand content effect, there is also an effect of the properties of the material where the surface area highly influences the paste needed to receive sufficient workability.

The gradation and type of aggregate: Powers is discussing about the essence in finding and using the optimal sand content. For combinations of three coarse aggregate fractions, changing the ratio between the two largest will not change the cement requirement significantly, provided that the optimum percentage of sand is used. However, when an arbitrary percentage of sand is used, the gradation of the coarse aggregate will be more essential regarding the cement content requirements. But, when a so called optimum sand percentage is used, the gradation of the coarse aggregate is much less important. The gradations requiring the least cement at a constant w/c-ratio are not necessarily those having the least void content. Crushed coarse aggregate requires higher percentage of sand and more cement for a given workability than natural rounded aggregate due to its higher surface area.

The factors influencing concrete workability described above indicate that concrete workability is influenced by a combined effect of many factors. Concrete workability is highly affected by the interaction between paste content, consistency of paste, sand content, water content and aggregate gradation. Changing one of them will affect the others because the amount of each of them is closely related to the others, which increases the complexity in concrete mix-design.

With the introduction of the third generation of superplastiziser, high water reducing agents (HWRA), solid particles in the paste could be dispersed without increasing the water content, i.e. sufficient paste workability could be received without a water content increase. The main effect of superplastiziser is to disperse agglomerated particles in the cement paste (Aitcin et al., 1994). HWRA has made it possible to compose workable cement pastes, viscous enough to carry the coarse aggregates which made it possible to produce self-compacting concrete. The demands on fresh SCC are different from those valid for normal vibrated concrete, which means that, except from the introduction of HWRA, the mix-design "rules" have been modified and further developed.

2.3 The paste layer theory

Kennedy (1940) introduced the "excess paste theory". It is a fundamental theory for understanding the close relation between paste and aggregate or mortar and coarse aggregate and its contribution to workability. The theory is based on the same principle described by Powers that solid particles must be suspended to some degree to receive sufficient workability. Kennedy stated that for concrete to be workable, the volume of cement paste must be, as minimum, equal to the volume of the voids in the dry aggregate skeleton. For any degree of excess of cement paste, the workability will be improved. Figure 2-1 illustrates the principle for the excess paste theory. If the voids around dry packed aggregate are filled with paste at exactly the same amount as the void volume, the aggregate will be in the same contact to each other as in the dry condition. It will result in high internal friction and unworkable concrete. If paste is added in a larger amount than the void volume, the aggregate particles will be forced apart and each aggregate particle will be surrounded by a layer of cement paste. The thickness of the paste layer surrounding each aggregate particle determines the degree of workability and is closely related to the surface area of the aggregate.

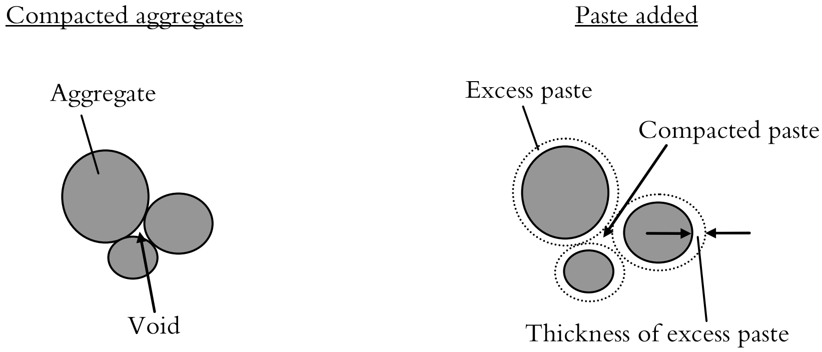


Figure 2-1 Principle for the excess paste theory, based on Kennedy (1940).

In addition, Kennedy also stated, that for any required workability, the amount of excess of cement paste depends on; 1) the consistency of the cement paste itself, lower water-to-cement ratios requires larger excess amounts and 2) the surface area of the aggregate, larger surface area means that greater cement paste excess is required.

Yen et al. (2000) used Kennedy's paste thickness theory on fresh SCC and divided the theory in two steps, 1) an overfilled mortar, i.e. an excess of paste coating the fine aggregate and 2) an overfilled concrete, i.e. an excess of mortar coating the coarse aggregate. Their results showed that the flowability of mortar increased as the paste coating thickness increased. It was also concluded that the increased rate of mortar flow was relatively small in a certain interval of paste layer thickness, which indicates that the upper limit of increased paste layer thickness effect has been reached, i.e. the mortar flow is not improved by any further increase of the paste layer thickness.

The slump flow of concrete was also tested on concrete with varying mortar workability. It could be seen that to reach a sufficient slump flow, concrete composed with mortars with low paste layer thickness, i.e. stiffer mortar, needed significantly higher mortar content than concrete composed with mortar with higher workability. The authors found a close relation between concrete slump flow and mortar slump flow for all overfilled ratios of mortar, which indicates that the fluidity of the mortar is strongly connected to the fluidity of the concrete if the excess paste theory was fulfilled.

For the performed tests, Yen et al. (2000) calculated the paste covering thickness as:

$$t = \frac{\left(V_g - V_v\right)}{\Sigma S} \qquad (1)$$

Where V_g=volume of cement paste or mortar, V_v= the void volume of packed aggregates, and ΣS=the total surface area of aggregates.

The volume of cement paste and the void content in packed aggregate are relatively easy to calculate. However, the surface area of the aggregate is complicated to calculate exactly. Particle shape and surface texture varies between different types of aggregate and it is difficult to estimate the total surface for a particular type of aggregate.

2.4 Characterization of the fresh properties

Self-compacting concrete can be seen as one type of concrete within "the concrete family". The meaning with this statement is that SCC shall fulfill equal performance as normal vibrated concrete (NC) regarding young and mature properties together with sufficient durability. The greatest difference between SCC and NC can be addressed to the fresh properties, where the demands on SCC are much higher and also more sensitive to external disturbance, i.e. less robust. Due to the higher functional requirements on fresh SCC, the key characteristics can be formulated, see for instance in Skarendahl et al. (2006), as:

- *Filling ability*; Complete filling of formwork and enclosing the reinforcement. Horizontal and vertical flow of the concrete within the formwork with maintained homogeneity.
- *Passing ability*; Passing of obstacles without blocking.
- *Resistance to segregation;* Maintain the homogeneity through mixing, transportation and casting. Both the requirements on dynamic stability and static stability shall be fulfilled.

In addition to these requirements, also opening time, pumping ability and finishing ability, form pressure and surface quality are mentioned as functional requirements for fresh SCC. All these fresh requirements shall also show a robust behaviour, and robust is generally defined as resistant to external disturbance. The most common outer disturbances in concrete production are the transportation time and the variations in water content. The effect on transportation time is reflected by the opening time. In concrete production, the moisture quote in the aggregate can be difficult to control exactly, which in practice might result in less or more water added than prescribed. It can easily be concluded that a proper SCC mix shall fulfill numerous of requirements in the fresh phase, which for a certain application might be almost an impossible task. It is thus wise to rank the requirements due to the actual apparent situation.

The filling ability shall be performed without any segregation of the constituents, and the concrete shall be able to pass through narrow spaces, e.g. reinforcement without blocking. These requirements can be used as a guideline for quality control when optimizing SCC because they will ensure that each essential property for fresh SCC will be satisfied.

Materials used in concrete (aggregate, cement, water, filler and superplastisizer), will affect the stated functional requirements in different ways. To succeed with a SCC mix-design it is of great importance to possess the understanding how these requirements are related. "General" rules have been proposed and reported earlier by some authors, and Ouchi et al. (1996) summarized the most general methods in SCC mix-design to fulfill these requirements, see Figure 2-2. Self-compactability is received by high flowability without segregation of the materials. Limiting the coarse aggregate and reducing the water to powder ratio will achieve high viscosity and avoid collision between the coarser particles. Adding superplastiziser will ensure the flowability of the viscous paste.

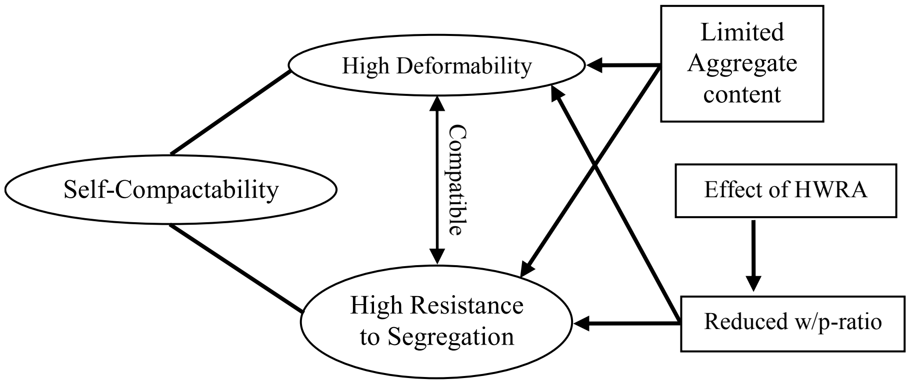


Figure 2-2 Methods to achieve self-compactability, After Ouchi et al. (1996).

To ensure proper filling ability, the concrete shall exhibit low resistance to flow (to ensure sufficient fluidity) and at the same time exhibit a moderate viscosity to maintain a homogenous concrete that not segregates. The most essential property to receive sufficient flow can be addressed to the properties and amount of the paste, which shall be flowable enough to transport the coarse aggregate when flowing, and the paste content shall be high enough to ensure that blocking does not occur. At the same time, the paste shall be viscous enough to ensure that no segregation of the coarse aggregate occurs. To fulfill these basic properties, the coarse aggregate is limited in comparison with normal vibrated concrete which will result in an increase of the total paste content.

2.5 Mix-design methods for self-compacting concrete

Since the middle of the 80th, when the Japanese first introduced self-compacting concrete, several mix-design methods have been proposed. Okamura and Osawa (1995 and 1996) can be seen as the pioneers in the SCC area, and their mix-design approach is the first generation of mix-design for SCC, i.e. the "original" optimization method can be addressed to the Japanese. It was proposed a mix design method performed on paste tests, then optimizing the mortar phase, and finally adjustments on the concrete level. Their main idea of conducting the test on paste and mortar was to examine the properties and compatibility of superplastisizer, cement, fine aggregate and pozzolanic materials. The major advantage with their method is that it avoids having to repeat the same kind of quality control test on concrete.

Okamura and Ozawa (1995) mean that the method to achieve self-compactability involves high deformability of the paste or mortar, and also high resistance to segregation between coarse aggregate and mortar when concrete flows through narrow sections.

Their suggested a mix-design method starts by avoiding blocking of the coarse aggregate when passing through narrow spaces. When the self-compacting concrete flows between reinforcement bars the relative location of the coarse aggregate is changed. This relative displacement causes shear stress in the paste between the coarse aggregate. Shear stress should be small enough to allow the relative displacement for concrete flowing through narrow passages. If the coarse aggregate contact exceeds a certain limit, then blockage will occur, no matter what the viscosity of the paste is (Okamura, 1997, Noguchi et al., 1999). In the method it is suggested that the coarse aggregate should not exceed 50% of the solid volume because a high volume of mortar is important to prevent blocking.

Further, they also suggest that the fine aggregate content shall be 40% of the total mortar volume, see *Figure 2-3a*. Due to Okamura, a decrease in deformability will occur caused by a direct contact between sand particles, if the fine aggregate content exceeds a certain limit.

In addition, the "Japanese method" emphasis the importance of a highly viscous paste to avoid blockage of the coarse aggregate, and the fluidity is then controlled by an efficient amount of superplastisizer *Figure 2-3b* (Okamura and Ozawa, 1995, Okamura and Ozawa, 1996, Okamura, 1997, and Okamura and Ouchi, 2003).

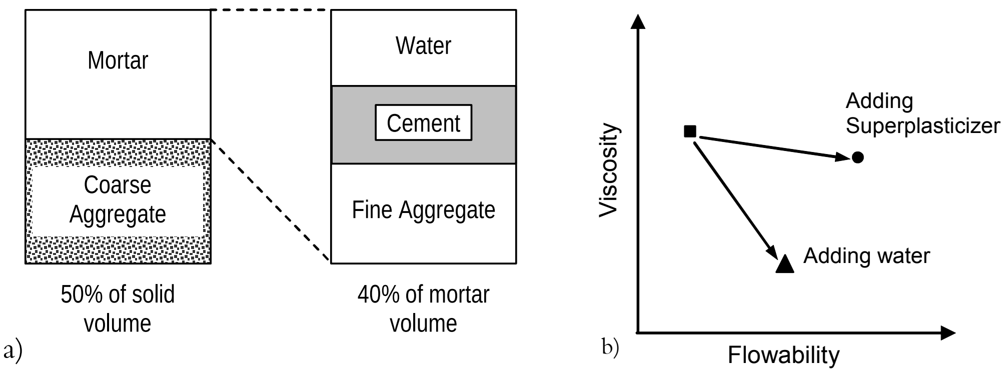


Figure 2-3 a) The effect of superplastisizer and b) Proportions of the constituents according to the Japanese method composing SCC suggested by Okamura (1997). After Okamura (1997).

The proposed "Japanese" mix-design method can be summarised as follows:

1) Coarse aggregate content is fixed at 50% of the solid volume
2) Fine aggregate content is fixed at 40% of the mortar volume
3) Water to powder ratio in volume is assumed as 0.9 to 1.0, depending on the properties of the powder

4) Superplastisizer dosage and the final water to powder ratio are determined to ensure self-compacting ability

The limitations in both the fine aggregate and the coarse aggregate content will result in SCC comprising relatively high cement paste content irrespectively from the properties of the available aggregate.

As seen above, the "Japanese" mix-design approach is performed on mortar and coarse aggregate separately. Ouchi et al. (1999) report about the importance of interaction between coarse aggregate and mortars particles, i.e. connecting the two phases with each other. The authors are explaining that, for equal amount and physical characteristic of a coarse aggregate, the difference in fine aggregate properties in the mortar will result in different properties of the concrete mix. They explain how the physical characteristics of fine aggregate and its content in mortar highly affect the interaction between coarse aggregate and mortar particles. In addition, Ouchi et al. (1999) based on results presented in Nagamoto and Ozawa (1997), conclude that for a specific concrete funnel speed, higher flow area and faster funnel speed of mortar is required in case of higher fine aggregate contents.

CBI (Swedish Cement and Concrete Research Institute) has proposed a SCC mix-design method based on the passing criteria (Petersson et al., 1996b, Petersson and Billberg, 1999). The method uses the least paste content needed to fulfill the demands on passing for a given reinforcement space. The effect of coarse river aggregate on the passing ability was studied. They found a relationship between blocking volume aggregate ratio, n_{abi}, and clear spacing to particles fraction ratio, c/D_{af}. With the established relationship, the maximum total aggregate content that not causes blocking could be calculated. The maximum allowed aggregate content is calculated corresponding to the ratio between coarse aggregate and total aggregate due to the blocking criteria. When the compositions and the content of the aggregate skeleton are chosen, the paste is composed in such way that it fulfills the remaining requirements for both fresh and hardened SCC. The CBI mix-design method makes it possible to calculate the minimum paste content that is acceptable for a specific free space between reinforcement. The blocking criterion was tested with a L-box described in Betongrapport nr 10 (2002) and the blocking criterion, i.e. the ratio of the height inside the column and at the end of the L-box, is 0.8.

Also Bui and Montgomery (1999) suggest a method based on the blocking criteria and minimum paste needed.

At Laboratoire Central des Ponts et Chaussèes (LCPC) equations were to describe the rheology, the filling ability and the segregation proneness based on the Compressive Packing Model (CPM). It is a development of the Solid Suspension Model (SSM). The required data for the computer calculations are the size distribution, the density, the packing density of the constituents and the saturation point of the superplastiziser (de Larrard and Sedran, 1994, Sedran et al., 1996, and Sedran and de Larrard, 1999). The flow behaviour was characterized with a concrete rheometer called the BTRHEO, which is developed at LCPC.

Su et al. (2001) and Su and Miao (2003) have developed a method for composing SCC, which is a mix-design method aimed for lower cement contents called medium strength self-compacting concrete. The general principle for their method is that the 28-day compressive strength is determined by the w/c-ratio and the cement content. The fluidity is received by the volume ratio of aggregate to binding paste in combination with the HWRA dosage.

Su et al. (2001) and Su and Miao (2003) start with the packing factor (PF) for aggregate (sand and gravel). The packing factor is defined as the ratio of mass of aggregate of tightly packed state in SCC to that of loosely packed state and the packing factor will thus affect the content of aggregate in SCC. A higher PF value generates a greater amount of coarse and fine aggregate, i.e. reduced content of binding paste, which will reduce the flowability and the compressive strength. If a lower PF value is chosen, the fluidity will increase for the same consistency of the binding paste. An increased amount of paste might also lead to increased drying shrinkage of the concrete and a rising cost of the material. The authors thus emphasis the importance in finding the optimal packing factor to meet required properties of the concrete. From a chosen packing factor, the amount of fine and coarse aggregate can be calculated. The remaining voids are filled with cement paste composed to meet requirements on strength and durability. The authors report on medium strength concrete with paste content in the range of 290-320 l/m^3, and a binder content that is approximately 370 kg/m^3, which is more economical. The authors are concluding that the packing factor is controlling the workability of fresh concrete and are suggesting that it shall be 1.16-1.18.

Toralles-Carbonari et al. (1996) present a three step mix-design method for high strength concrete. They base their method on the assumption that the workability of the concrete mainly depends on the fluidity of the paste and that the optimum aggregate skeleton is determined due to the least volume of voids. They suggest that the fluidity of the paste and its corresponding superplastiziser dosage can be evaluated with a March cone test, and the paste is defined as cement, water, mineral additives and superplastisizer. The paste test starts with finding an optimal dosage of superplastiziser where the so called "saturation point" is found with the Marsh cone test. The saturation point can be defined as the point beyond which the fluidity does not benefit from any addition of superplastisizer. The aggregate phase is optimized by packing the dry aggregate which receives the aggregate composition with the least void content. The mixture with the least void content is considered as the optimal sand/gravel ratio. This quote is used when the aggregate grading curve is chosen for further use in the concrete matrix. The last step in their suggested mix-design method is to find an optimum paste content to receive sufficient fresh properties of the concrete mix. The basic approach is that the minimum paste content needed to ensure workability and strength shall be used. The void content in the aggregate skeleton is thus overfilled with cement paste, due to the excess paste theory, to ensure sufficient workability.

An extended study on the fluidity of cement pastes characterized with the Marsh cone test have been performed by Agullo et al. (1999). They concluded that important information about the flow properties of cement paste can be interpreted with the Marsh cone test. The method is a simple and useful tool to characterize the fluidity and to select appropriate combination of materials, interpret the effect of mineral additives, find the optimal superplastiziser dosage and also interpret the fluidity loss with time.

Gettu et al. (2002) have developed a four step mix-design model for high-strength SCC. Their basic assumption is to consider concrete as a two phase material, paste and aggregate. The paste optimization is based on the method described in Toralles-Carbonari et al. (1996) where Gettu is one of the authors. In the second step, the mini-slump is used to choose the optimal fly ash dosage, which will result in a paste composition with the prescribed water-to-cement ratio. The mini-slump tests are performed with different fly ash to cement ratios, with a fixed SP dosage decided from step one. The optimal spread is chosen to 180mm, which has been suggested by Gomes et al. (2001) to give a paste with satisfactory fluidity. The aggregate is optimized due to the degree of packing, where loose packing is used. The combination with the minimum void content is chosen as the optimum sand/gravel ratio. The aggregate and the paste are then assembled into a concrete matrix adjusted with some trial mixes.

The literature review shows that a lot of different mix-design methods exist to produce a SCC mix with sufficient properties. Domone (2006a) has analyzed 68 case studies where self-compacting concrete has been used between 1993 and 2003. All of the studied mixes have been used successfully within their application area and they have been produced with different constituents, i.e. locally available materials, and in different proportions. The author is summing-up the most common mix proportions and constituents from these cases; Lower coarse aggregate contents, increased paste content, high powder contents, low water/powder ratios, high superplastiziser dosage and in some cases a viscosity-modifying agent. Domone (2006a) has also listed the key proportions as coarse aggregate content, paste content, powder content, water/powder ratio and fine aggregate/mortar content. It could be seen that coarse aggregate, paste content and fine aggregate to mortar content showed the smallest spread in content among the different mixes. This might indicate that these three key properties are the most essential for a successful self-compacting concrete, while powder content and water to powder ratio give more flexibility. From the evaluation of the different SCC mixes performed by Domone (2006a) it was observed that the median value for the coarse aggregate content was 31%, the paste content was 35% and the fine aggregate to mortar content was approximately 47%, but also these three properties are spread around the median value. This indicates that it is possible to produce a well working SCC with higher fine aggregate content than it has been proposed earlier, where the fine aggregate to mortar content are said to be fixed to 40%. It can be seen that the fine aggregate to mortar ratio is ranging between 38% and 54% for the evaluated mixes.

Among these 68 investigated mixes, the powder contents have varied between 425 and 625 kg/m^3, which indicates that the older recommendations, powder content in the range between 500 and 530 kg/m^{3}can be questioned. It can be suspected that the powder content needed for a certain mix is more dependent of the combination and properties of the other ingoing materials, than keeping it at a fixed value. The powder content and the fine aggregate to mortar content are closely related. Increasing the latter will result in an increase of the fine aggregate content or a decrease of the powder content. Domones investigation indicates that it is possible to take advantage from the fine aggregate properties in a larger extension than it has been proposed from earlier mix-design methods, which can make it possible to lower the powder content needed. Domones investigation also indicates that it is conservative to fix the amount of certain constituents because it can be seen that it is possible to succeed with a SCC mix with a very wide range of amounts of the different ingoing materials.

Figure 2-4 illustrates a SCC mix composed due to the median value of the key proportions that was found in Domones investigation. The fine aggregate is defined as aggregate particles passing the 4mm sieve and the coarse aggregate is particles larger than 4mm. The maximum size of the coarse aggregate has varied between 16 to 20mm.

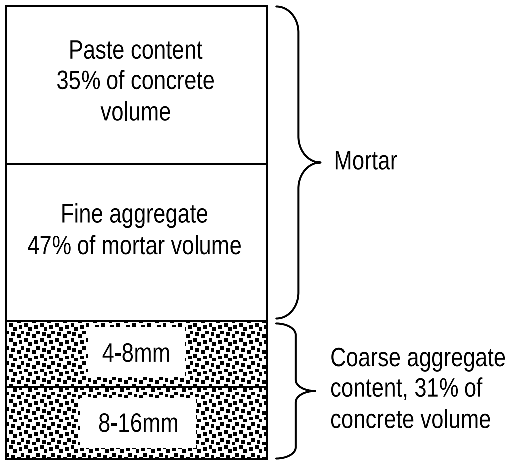


Figure 2-4 A self-compacting concrete mix, composed due to the median values of the key proportions found in Domone (2006a).

Some mix-design methods are based on the assumption that one or more of the constituents shall be fixed or limited. By settle the amount for some of the constituent already in the staring point, the proportions of the different materials might be not fully utilized. They might not take advantage from the characteristics of the ingoing materials. It is probably possible to produce more cost-effective self-compacting concrete if the amount of the key constituents is free to vary within a larger extent, which can be obtained by taking the advantage from their particular properties into consideration.

Within the Brite Euram project, Brite EuRam Proposal No. BE96-3801 Task 9, Tviksta (2000) the following general requirements in SCC mix design is listed:

A high volume of paste: the friction between the aggregates limits the spreading and the filling ability of SCC, which is avoided by an increased content of paste (cement + additions+ efficient water + air), approximately 330 to 400 l/m^3.
High volume of fine particles (<80 μm): to ensure sufficient workability and also limiting the risk of segregation or bleeding, SCC contains a large amount of fine particles

(around 500 kg/m3). Portland cement is often replaced to some degree to avoid excessive heat generation. Commonly used replacement materials are mentioned as: mineral admixtures like limestone filler or fly ash.
A high dosage of superplastiziser: The third generation of superplastiziser is introduced in SCC to ensure high fluidity without segregation.
A low volume of coarse aggregate: It is possible to use natural rounded, semi-crushed or crushed aggregates to produce SCC. The coarse aggregate plays an important role on the passing ability of SCC in narrow sections and the volume is thus limited. The maximum aggregate size, Dmax , is between 10 and 20mm. The passing ability decreases when Dmax increases, which leads to a decrease of the coarse aggregate content
The possible use of a viscosity agent (water retainer): These products have the same role as the fine particles: minimizing bleeding and coarse aggregate segregation by thickening the paste and retaining the water in the skeleton. The introduction of such products in SCC might be important in the case of SCC with high water to binder ratio, e.g. house building applications.

Even though several suggestions for SCC mix-design exist, as explained above, some general rules can be established and these can be, according to EFNARC (2005), summarized as:

- Low water to powder ratio increases the viscosity of the cement paste, which is important to ensure that the coarse aggregate does not segregate.
- Limited coarse aggregate content is often mentioned as an essential parameter to manage the criteria on passing ability.
- Increased paste content is an effect of limited coarse aggregate content. The increased paste content shall ensure that no blocking occurs.
- Use of superplastisizer to ensure sufficient workability. The effect of a superplastiziser varies between different brands and also due to how they are combined with cement and mineral additives.

2.6 Test methods and classification of SCC

2.6.1 Describing SCC in terms of rheology

Professor Bingham of Lafayette College invented the term ”Rheology” and it is defined as “*the science of the deformation and flow of matter*”, which means that it is concerned with relationship between stress, strain, rate of strain and time. This definition is very wide; in practice rheology is concerned with materials whose flow properties are more complicated than those of a simple fluid (liquid or gas) (Tattersall, 1983). Rheology has been applied to describe the properties of fresh concrete where rheological measurements will provide important information about the effect of the mix composition and the flow behaviour. The simplest way to describe the relation between shear stress and shear rate for more complicated materials is by a straight line that not passes through origin, the Bingham model. The inclination of the straight line is defined as the viscosity. To initiate the flow there is a minimum stress, the yield value, and no flow will occur below that value.

According to Wallevik (2003) the yield value for SCC is ranging from 0 to 60 Pa and the viscosity is in the interval 20 to 100 Pas, as a general definition. These two parameters are closely related to ensure the homogeneity of a SCC mix. If the yield value has a certain value, then the viscosity shall have a significant value to obtain sufficient fresh properties. Shortly, when the viscosity is high the yield value shall be low and when the yield value is high the corresponding viscosity shall be lower. In normal vibrated concrete, the yield value is relatively high which will prevent the larger particles from sinking. In SCC when the yield value is close to zero, these restraining forces are not present. It means that the viscosity of the concrete must ensure that the concrete remains stable without segregation. Wallevik (2003) also explains the need for even higher viscosity in case of gap graded aggregate because of the lack of lattice effect.

The rhelogical parameters are tested with a viscometer and different types of commercial viscometers are available for concrete, e.g. the BML-Viscometer (Wallevik, 2000), and the BTRHEOM (De Larrard et al., 1998).

Further on, Wallevik (2003) proposes how the workability can be classified regarding its rheological values illustrated in a yield value – viscosity diagram, see *Figure 2-5*. The recommended values are, according to Wallevik, within the inner box. In addition, Wallevik also suggests an necessary slump flow depending on the plastic viscosity to achieve self-compacting concrete. If the viscosity increases, the slump flow must also increase to ensure that the concrete is self-compactable.

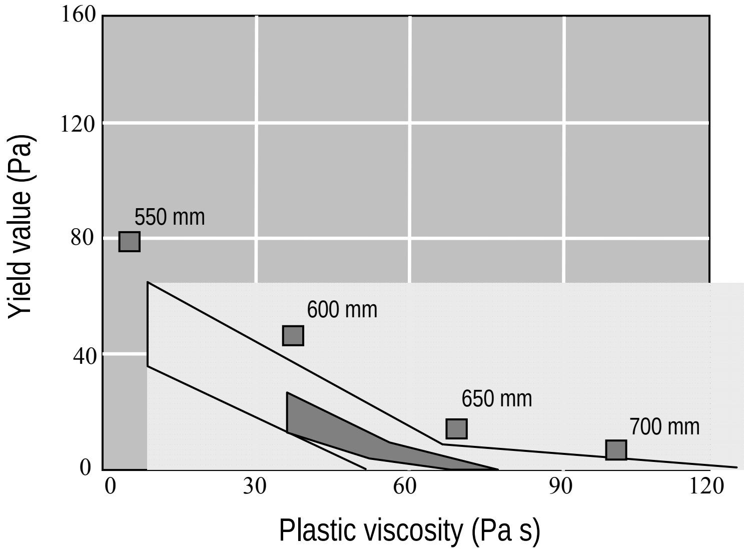


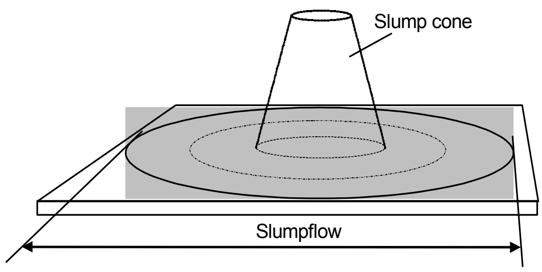
Figure 2-5 Proposed target area for SCC and corresponding slump flow, after Wallevik (2003).

Rheology as a tool to characterize the fresh properties of SCC will not be applied within the frames of this thesis. The theories behind the science of rheology will thus not be treated any further or deeper.

2.6.2 Classify the flow properties with practical test methods

Tests, if useful, shall simulate the actual behaviour of concrete that occurs when placed in the formwork. They shall also cover the three key characteristics; filling ability, passing ability and resistance to segregation. During the years of SCC-development some practical and field oriented tests methods have been proposed where each of them is aimed to control and describe one or more of the fresh functional requirements. Commonly used practical test methods to characterize the fresh properties are; the slump flow test, T50, V-funnel test, L-box, and sieve test for interpreting the resistance to segregation, see e.g. Betongrapport Nr. 10, Petersson (1998b), and Testing SCC (2005).

The slump flow is performed with Abram's cone. The cone is filled with concrete and when it is lifted, the concrete will flow out by its own weight forming a circle, as illustrated in Figure 2-6. The diameter of the final spread is the measured slump flow. In addition to the slump flow, the time taken for the sample to reach a diameter of 500mm is measured, which is defined as T50.



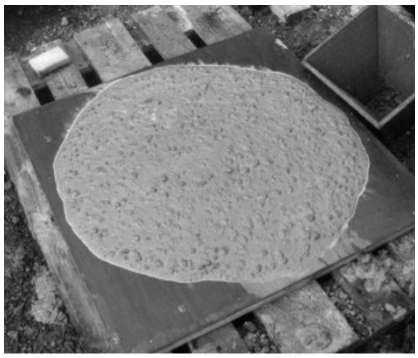


Figure 2-6 The slump flow test is performed with Abram's cone and the test sample forms a circle and its diameter is measured, i.e. the slump flow.

The V-funnel test is performed with a V-shaped funnel, as illustrated in Figure 2-7. The time needed for the concrete to completely flow out of the funnel is measured.

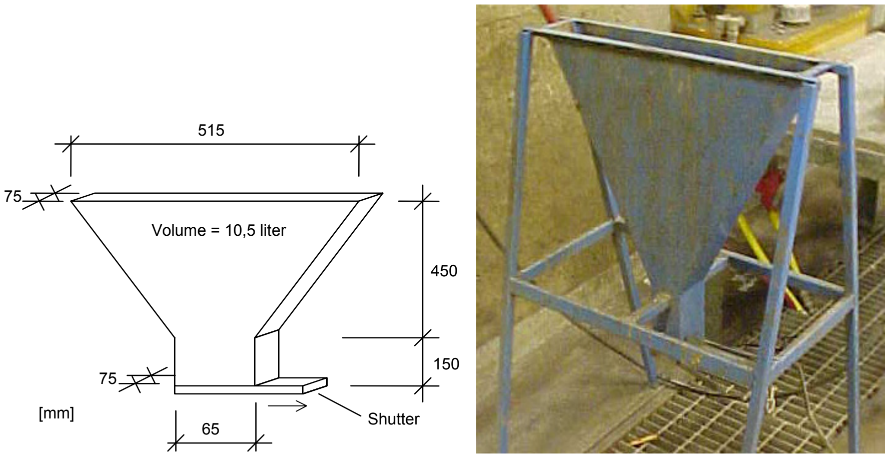


Figure 2-7 A V-funnel used in the V-funnel test.

The European guidelines for SCC, (EFNARC, 2005), have formulated the fresh characteristics and related appropriate test methods to ensure its quality, Table 2-1.

Table 2-1 Test methods for the key characteristics according to The European guidelines for SCC, (EFNARC, 2005).

Characteristic	**Preferred test method(s)**
Flowability	Slump-flow test
Viscosity (assessed by rate of flow)	T50, Slump-flow test or V-funnel test
Passing ability	L-box test
Segregation	Segregation resistance (sieve) test

2.6.3 Workability in relation to application area

Test methods to verify and ensure sufficient quality regarding the fresh key properties is essential for SCC. The three key characteristics, filling ability, passing ability and resistance to segregation can be assessed with different kinds of practical test methods and normally, a combination of test methods is used to classify a SCC mix. Utsi (2003) is reporting about the idea of classify a SCC mix with the use of two different workability test methods, e.g. V-funnel time with slump flow or the V-funnel time together with the T50 time. However, specific requirements on fresh SCC are mainly depending on the type of application where different types of applications call for different kind of consistencies. EFNARC is summering the most important parameters affecting the fresh requirements as; conditions related to the concrete element geometry, the quantity, type and location of reinforcement, inserts, cover and recesses, placing equipment, placing methods and finishing method. Further, EFNARC is suggesting a classifying system comprising slump flow classes and viscosity classes, see Table 2-2.

Table 2-2 Slump flow classes and viscosity classes suggested in EFNARC (2005).

Class	**Slump flow, mm**
SF1	550 to 650
SF2	660 to 750
SF3	760 to 850

Class	**T50, s**	**V-funnel time, s**
VS1/ VF1	≤ 2	≤ 8
VS2/ VF2	> 2	9 to 25

However, consistency classes become useful when they are connected to an application area. Walraven (2003) proposes that different kind of SCC mixes, regarding the fresh properties, shall be used for different kind of applications. The author suggests consistency classes where slump flow together with the V-funnel time will get a classification system. The author has roughly divided some frequently used application areas in different classes and proposes target values for each application, see Figure 2-8.

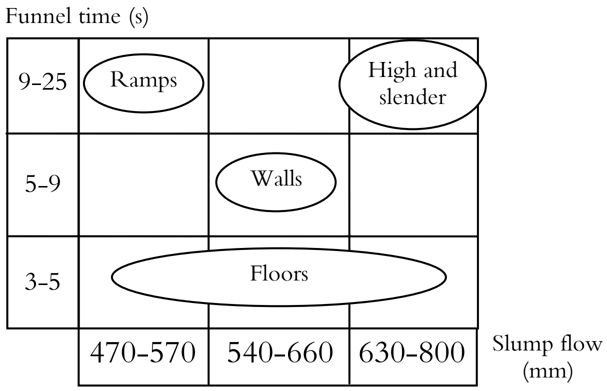


Figure 2-8 Application areas in relation to SCC properties. After Walraven (2003).

In Hwang et al. (2006) a performance based specification for quality control of SCC is suggested. They are suggesting target values for the most commonly used test methods aimed for some of the most common structural applications. The authors are also discussing how different test methods can be combined to predict one or more of the three functional requirements.

Using consistency classes and performance based specifications for fresh SCC are important to ensure sufficient quality and it will probably improve the cost-efficiency because a proper workability will facilitate the casting process. A further extension of performance based concrete is to choose the composition of the available materials in a way that they meet the stated requirements on a given workability.

2.7 Concluding remarks

From the reviewed literature some important aspects can be summarized for further consideration of interest for the work performed in this thesis.

First of all, it can be concluded that the main differences between a self-compacting concrete mix and a conventional concrete mix can be addressed to the fresh properties. The main difference in mix-design for SCC can generally be summarized as:

- Lower coarse aggregate content
- Increased paste content
- High powder content (materials < 0.125mm)
- Low water to powder ratio
- Incorporation of a high water reducing agent (3rd generation of superplastisizer)

Fresh concrete as a material can be regarded as solid particles suspended in water. An unworkable concrete mix is when the particles are locked together forming a rigid structure. The mobility occurs when all of the solids are suspended in water and having freedom to move. It is also a function of the force of surface tensions, i.e. high particle surface exposed to water will increase the total tension in the mix which will stiffer the mix. With the introduction of the third generation of superplastiziser, high water reducing agent, solid particles in the paste could be dispersed without increasing the water content, and it became possible to compose workable cement pastes, viscous enough to carry and transport the coarse aggregate.

The most important factors influencing the concrete workability can be summarized as:

- The quantity of the paste
- The properties of the paste
- The characteristics of the aggregate

These three factors are material related where different types of materials will influence them differently. The structure of concrete, solid particles suspended in water, can be regarded by dividing the particles into different phases, which all interplay with each other.

1) cement paste; cement, water, mineral additives and superplastiziser
2) mortar or micro mortar; cement paste and the finest part of the aggregate
3) concrete; coarse aggregate suspended in mortar or micro mortar.

The properties of the paste are a function of the amount of solid particles in comparison to the water content and also related to the properties of the particles, e.g. characterized by specific surface area and particle shape. The quantity of the paste in mortar phase will ensure the mortar workability and is a function of the fine aggregate properties in combination with the properties of the paste. The coarse aggregate shall finally be suspended in mortar or micro mortar with sufficient workability where the degree of workability is a function of the micro mortar content, i.e. excess of mortar or micro mortar in coarse aggregate. Workability of concrete is thus a function of 1) mortar workability; excess of cement paste in the fine aggregate and 2) concrete workability; coarse aggregate overfilled with mortar or micro mortar.

Mix-design can thus be regarded due to this chain of material related parameters, which all are important by themselves and when mixed together will form a concrete composition. The main purposes with a concrete mix-design method are to fulfill these main factors for the available materials in a manner that is appropriate for the structure.

3 THE λ_{25} MIX-DESIGN METHOD

3.1 Introduction

Referring back to section 2.7, mix-design shall be performed in a manner that makes it possible to evaluate how the available materials shall be combined to receive appropriate properties. From chapter 2 it can be concluded that it is possible to succeed with a self-compacting concrete mix in a wide spectra of proportions between the constituents. It has been reported that a well working SCC can be produced with a powder content ranging from 445 to 605 kg/m^3, which is a relatively large spread. In addition, it has been shown that no ultimate amount of the constituents exists to succeed with SCC, which is probably an effect of the importance of taking both the properties of the available materials and the application area into consideration when composing SCC. A mix-design method that makes it possible to choose appropriate combinations of the available material with respect to demanded workability and performance can thus increase the possibility to produce more cost-effective concrete. If the properties of each constituent are utilized as much as possible, the chance to succeed with a SCC mix within reasonable economical frames will probably increase.

3.2 Basic definitions

As mentioned in chapter 1 and 2, fresh concrete can be regarded as solid particles suspended in water. However, depending on particle size, type and its influence on the concrete properties, for some reasons it can be simpler to regard concrete in different phases during the mix-design process, which all are closely related. The following definitions are used here:

Concrete: water, cement, mineral additives, superplastiziser, fine aggregate and coarse aggregate.

Paste: water, cement, mineral additives and superplastiziser

Micro mortar: cement, mineral additives, superplastiziser and fine aggregate particles from 0 to 0.25mm

Mortar: cement, mineral additives, superplastiziser and fine aggregate up to the size limit for fine aggregate.

Aggregate: all aggregate particles ranging from 0 to the maximum grain size where fine aggregate is defined as 0-4mm and coarse aggregate is defined as particles >4mm.

It can be concluded that the phases are closely related, e.g. parts of the aggregate and the paste is both a part of the micro mortar. The definition is made on a technical basis, which facilitates the possibility to trace and evaluate the effect from different types of material on the total concrete behaviour.

3.3 Method and basic assumptions

A micro mortar optimization method and an aggregate optimization method is proposed and fully described in the appended papers A and B. The most essential parts from these two papers are briefly described here, where focus is on how to use received information in concrete mix-design. The proposed method is developed based on a pragmatic perspective. It is an experimentally based concrete mix-design method with the main focus held on how material related properties, important for the fresh concrete, can be evaluated, and how received information can be used for concrete production. The effect on concrete properties from the available materials and how a mix shall be chosen regarding its field of application has thus been in focus. Material characterization methods are chosen regarding their simplicity to both procure and use because the suggested method shall be able to adopt without expensive laboratory equipments.

The mix-design method proposed in is based on the following assumptions:

- Concrete can be regarded in different phases, defined in section 3.2, which are closely related. Properties and amounts from one phase are in direct relation to another phase, which means that the connection between different phases to a concrete mix is an essential part.
- The main effect of superplastiziser is to disperse agglomerated particles in the cement paste (Aitcin et al., 1994). The agglomeration is a result of several types of interactions; Van der Waals interaction between particles, electrostatic interactions and interactions involving water molecules (Legrand and Wirquin, 1992). The effect of superplastiziser on the finest particles in concrete, i.e. the micro mortar, are here experimentally evaluated and optimized based on workability tests, here performed with a Marsh cone test together with a mini slump test.
- The finest part of the aggregate will consume both water and superplastiziser and will thus influence the fresh mortar properties.
- The excess paste theory is applied in two steps and experimentally evaluated; 1) The micro mortar shall contain an excess of cement paste to ensure sufficient workability and 2) the mortar or micro mortar shall overfill the coarse aggregate to ensure sufficient concrete workability.
- Powers theory that there is a most appropriate fine aggregate content for a given water to powder ratio is here applied by packing tests in combination with a defined connecting parameter λ_{25}.

3.4 Regarding concrete in different phases

The micro mortar phase and the aggregate phase are here suggested to be optimized separately. It facilitates the possibility to ensure workability step by step from the paste phase via micro mortar, which includes the combined effect of paste and fine aggregate, to a concrete matrix. The proposed method makes it possible to evaluate the effect of cement paste on micro mortar, and then combining the micro mortar to the aggregate skeleton by a material based relation.

When regarding SCC as a two phase material, a common approach is to use paste tests to find the optimal superplastiziser dosage for a given combination of cement and mineral additives. The received combination is then added to an aggregate skeleton chosen due to some demands, often based on its maximum degree of packing. The optimized paste is then added to the total aggregate skeleton and overfilled to receive sufficient workability. Domone (2006b) is proposing how mortar fluidity, tested for a given amount of fine aggregate, can be interpreted with the Marsh cone test together with the mini slump test.

However, paste tests performed that excludes the fine aggregate will be difficult to translate and use in a concrete mix, since the finest part of the aggregate, according to Powers (1932), also influence the water and superplastiziser demand needed for a certain workability. However, even if the fine aggregate are included in the paste tests, and then denoted mortar or micro mortar, its relevance will only be valid if the proportions of the constituents chosen from the micro mortar tests can be further translated and used in a concrete mix. To further increase the relevance and thus increase the potential in performing micro mortar tests, it is favourable if the fluidity can be interpreted and chosen with respect to the actual field of application.

The most essential part when working with phases separately is thus identified as:

1) the phase comprises the finest particles in concrete shall include all particles in the chosen size area, i.e. cement, mineral additives, water, superplastiziser and the finest part of the aggregate.

2) it shall be able to translate the proportions of the constituents and its corresponding properties chosen in one phase to a concrete mix.

3) the highest potential can be reached if the available materials can be combined to fulfill a demanded workability, based on the structural element to be cast.

The micro mortar optimization method and aggregate optimization method proposed in this thesis are both designed in a manner that makes it possible to directly connect the micro mortar phase with the aggregate phase with retained proportions of the constituents. A connecting parameter, called λ_{25}, has been introduced, which describes the relation between the finest part of the fine aggregate and the total content of cement and mineral additives. This parameter is shown to be one of the key parameters both for the micro mortar properties and when combining the constituents to a concrete mix.

3.5 Traditional mix-design of concrete

Concrete mix-design means a method to choose the constituents in different amounts in order to achieve a concrete mix with sufficient properties for the current application. The mix shall fulfill demands in fresh, young and hardened phase. The most common mix-design method used in Sweden is based on Alexanderson och Buö (1970). The basis is the demands on compressive strength where the water-to-cement ratio law stated by Abrams (1918) is used to receive a particular strength requirement and in addition, air content is chosen regarding stated demands. Concrete is regarded as two different phases; cement paste volume and aggregate volume. All constituent volumes are here expressed as m^3 (constituent)/m^3(concrete) or simply a dimensionless ratio. The sum of all constituents is the concrete mix, which gives

$$V_p + V_{agg} = 1 \quad (2)$$

where

V_p = cement paste volume, -

V_{agg} = aggregate volume, -

$$\begin{aligned} V_p &= V_c + V_W + V_{air} + V_{add} \\ V_{agg} &= V_{fa} + V_{ca} \end{aligned} \quad (3)$$

where

V_c = cement volume, -

V_W = water volume, -

V_{air} = air content, -

V_{add} = volume of additves, -

V_{fa} = fine aggregate content, -

V_{ca} = coarse aggregate content, -

The total aggregate volume is defined as the sum of each aggregate grain and is calculated by dividing the weight of the dry material with the density, normally 2650 kg/m^3. The proportioning of the constituents is commonly expressed as;

$$V_c + V_W + V_{air} + V_{add} + V_{agg} = 1$$

which can be rearranget to (4)

$$\frac{m_c}{\rho_c} + \frac{m_w}{1000} + V_{air} + \frac{m_{add}}{\rho_{add}} = 1 - \frac{m_{agg}}{\rho_{agg}}$$

where

m_c = cement content, kg

m_W = water content, kg

m_{add} = content of additves, kg

m_{fa} = fine aggregate content, kg

m_{ca} = coarse aggregate content, kg

δ_c = density cement , kg/m^3

δ_W = density water, kg/m^3

δ_{add} = density of additves, kg/m^3

δ_{fa} = density of fine aggregate, kg/m^3

δ_{ca} = density of coarse aggregate, kg/m^3

The law of water-to-cement ratio, Abrams law, is an accepted tool to choose appropriate amount of cement and water to receive a demanded compressive strength. Aggregate are often divided into different fractions, fine and coarse aggregate. The mutual proportion between these two is based on the total grading curve, demands on workability and properties of the chosen aggregate.

As a basic mix-design approach Alexandersons method can be used also in case of SCC with adjustments in the proportions between the constituents in comparison to normal vibrated concrete. The challenge with SCC mix-design is to know how to choose appropriate combinations and proportions between aggregate, cement, water and mineral additives to fulfill stated demands on fluidity and performance.

3.6 Method to choose an appropriate micro mortar

3.6.1 Introduction

The experimental method for micro mortar optimization is presented in appended paper A, "A Performance based experimental micro mortar optimization method for SCC". The most important results for further implementation in concrete mix-design are summarized and described here.

The main objective with micro mortar optimization is to investigate how the available materials shall be combined to receive appropriate fluidity and robustness. The micro mortar is aimed to be optimized regarding the available materials together with an evaluation of the fluidity. In addition, the chosen proportions of the constituents and the corresponding flow properties shall be reflected in the total concrete matrix, with the connecting parameter λ_{25}.

The suggested method is a systemized method of working with the smallest particles in concrete to obtain adequate information regarding the micro mortar composition and its corresponding properties. It is based on simple test methods, the mini slump test and the Marsh cone test. The Marsh cone test is commonly used within the cement and petroleum industry to compare the fluidity of different grouts (Aitcin et al., 1994).

A structured method for how the fluidity can be interpreted and characterized, regarding available material and field of application, is proposed. The work has been performed with the aim to facilitate the translation from micro mortar tests to a concrete mix. The intended potential with the suggested method is that a potential user can interpret, from very simple test methods, different combinations of constituents regarding fluidity and robustness to form a basis for decisions regarding the optimal combination of materials.

3.6.2 Definition and description of the key parameter λ_{25}

One principle to produce well working self-compacting concrete is known by using a large amount of fine materials, i.e. a large excess of cement paste. The paste provides fluidity and cohesion and shall transport the coarse aggregate without segregation and is considered to largely affect the workability of the fresh concrete. It is thus of great importance that the paste is well combined and robust to meet these demands. The cement paste in SCC consists of cement, water, superplastisizer and a mineral additives with an approximately grain size of 0-0.100mm. However, also the fine aggregate consists of particles with grain sizes similar to the sizes of filler and cement. It can thus be assumed that the finest particles in the fine aggregate also will influence the properties of the paste regarding the demands on water and superplastisizer and its corresponding fluidity. Paste tests performed only comprising cement, mineral additives, water and superplastisizer can be difficult to translate properly to concrete because of the lack of information about the influence from the fine aggregate. It is thus more convenient to perform tests on micro mortar including all particles smaller than a chosen limit; water, cement, mineral additives, finest part of the aggregate and superplastisizer. The grain size limit is chosen to 0.25mm in the proposed test method, which has earlier been used by e.g. Billberg (1999b). Mørtsell et al (1996) define the micro mortar matrix as all particles smaller than 0.125mm. Since parts of the fine aggregate shall be separated from the total aggregate volume, a higher size limit will facilitate the handling of materials in the sieving process, which is the main reason for the chosen limit.

When optimizing concrete in different phases, it is essential that the phases are optimized and composed in a manner to be able to transform the results from each phase in the total concrete matrix. Tests must thus be designed in such a way that the results can be interpreted regarding both the total content of binder and mineral additives and the fine aggregate content for further assembling with the aggregate skeleton.

Each type of fine aggregate contains an amount of particles smaller than 0.25mm, which can be evaluated from the grain size curve. For concrete mix-design purposes it means that the content of the fine aggregate in the concrete mix are in direct relationship with the amount of the finest aggregate particles in the micro mortar as illustrated in Figure 3-1. The absolute amount of fine aggregate will result in an absolute amount of aggregate particles ranging between 0 and 0.25mm, here denoted as A_{25}. The absolute content of cement and mineral additives is related to the total paste content in the concrete. It means that the proportions between cement, mineral additives and A_{25} are an effect of both the total paste content and the total fine aggregate content. If the fine aggregate content is increased or decreased, it will thus affect the properties of the micro mortar significantly.

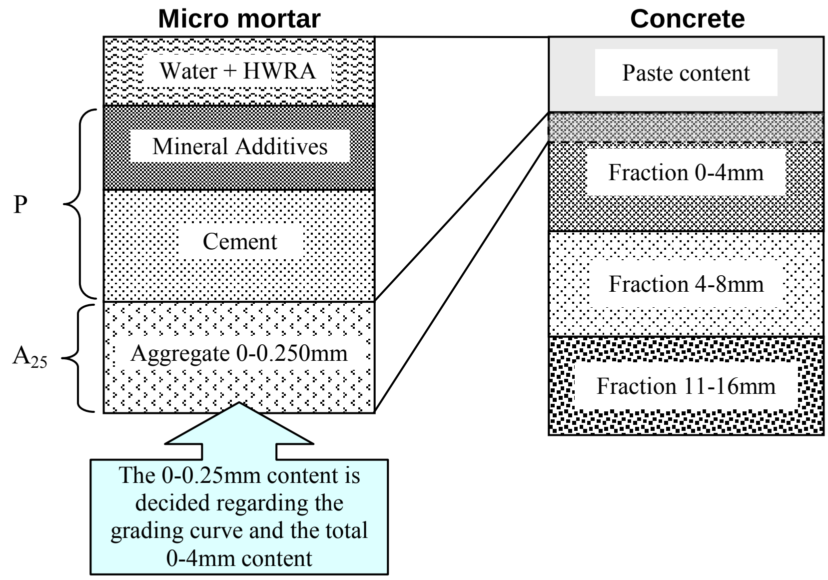


Figure 3-1 An illustration of the relationship between the micro mortar phase and the dry aggregate skeleton.

To fully utilize the potential with micro mortar optimization it is desirable that they can be performed and interpreted independent from the absolute contents when used in concrete. In addition, they shall also be performed in such a way that the chosen combination of materials is reflected in the concrete, which will facilitate the connection between the micro mortar phase and the aggregate phase when assembled to a concrete mix. To fulfill these criterions the following parameter definition for micro mortar tests with the fine aggregate to binder quote, $\lambda_{25,}$ is suggested:

$$\lambda_{25} = \frac{A_{25}}{P}$$

where: A_{25}= Aggregate content of particles in the range 0-0.25mm, [kg], and P= Total content of powder materials (sum of cement and mineral additives (cement, filler fly ash, silica fume)), [kg]

If the tested λ_{25}-quote is kept constant when added to concrete, the results from the micro mortar tests are independent from the chosen paste and fine aggregate content in the final concrete mix. It also admits a direct connection to the chosen aggregate grading curve; for a chosen fine aggregate content, the total binder content can be calculated to retain the tested λ_{25}-value.

The method proposed in paper A makes it possible to characterize the flow properties, evaluate the robustness and the point of separation for different combinations of available materials.

3.6.3 Results and interpretation of a micro mortar test

The Marsh cone flow time shows a typical behaviour as a function of superplastiziser dosage. At small dosages the micro mortar mix is very viscous and flow very slowly out of the funnel. At a relatively distinguish point the flow time becomes fast through the funnel, which is defined as the saturation point (Aitcin et al., 1994 and Sedran et al., 2000). Beyond the saturation point the Marsh cone flow time does not decrease any further, i.e. the flow is not improved significantly by addition of superplastisizer. The saturated Marsh cone flow time is depending on how the mix is composed. For instance, lower w/p-ratios will result in higher Marsh cone flow time than higher w/p-ratios. Each saturation point corresponds to a mini slump flow, which is illustrated in Figure 3-2. The mini slump flow can be further increased by adding superplastisizer but at the same time the point of segregation will come closer. It is thus wise to choose flow properties that are closer to the saturation point than the point of segregation. In paper A the so called "buffering zone" was introduced, which is defined as the interval between the saturation point and the point of segregation. A longer buffering zone is preferable because it might be an indication of that the mix is more insensitive against superplastisizer dosage.

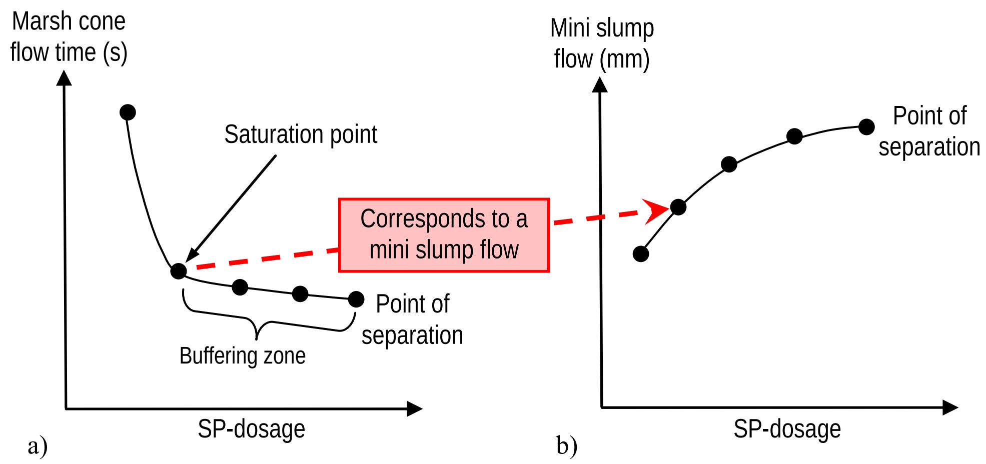


Figure 3-2 a) Illustration of a typical behaviour in the Marsh cone test. The saturation point can be interpreted and corresponds to a mini slump flow value, as illustrated in figure b.

It has been concluded in paper A that a given w/p-ratio corresponds to an upper and a lower λ_{25}-value, i.e. for the specific material a maximum and minimum A_{25} content exist for a given water to powder ratio, see Figure 3-3. For the λ_{25}-value and w/p-ratio correlation it can generally be said that higher w/p-ratios must be combined with higher λ_{25}-values and lower w/p-ratios must be combined with lower λ_{25}-values to receive sufficient fluidity, but the absolute values and correlation are material related.

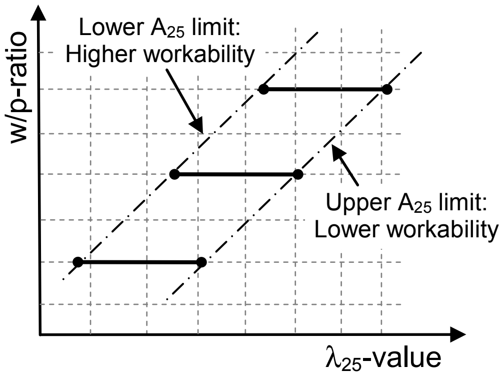


Figure 3-3 Schematic illustration of how the water to powder ratio is related to the fine aggregate content (λ_{25}-value).

The fresh micro mortar properties, taken from the saturation point in the Marsh cone test, and its corresponding mini slump flow value will change while the λ_{25}-value changes between the upper and the lower limit within each w/p-ratio group. The upper λ_{25} limit for each w/p-ratio corresponds to a more short flowing concrete with a rate of flow that will increase for higher w/p-ratios. The lower λ_{25} limit corresponds to a micro mortar with faster flow and larger spread. It gives some possibilities to choose the proportions of the constituents to receive a certain workability. For practical purposes it means that the fresh concrete properties can be controlled by changing the λ_{25}-value or by changing the w/p-ratio. The w/p-ratio is mainly controlled by the demands on water-to-cement ratio together with the total powder content needed to ensure the workability. The λ_{25}-value can be controlled by the total amount of fine aggregate content where higher fine aggregate contents will result in higher λ_{25}-values in case of constant paste content.

A chosen λ_{25}-value is closely related to the aggregate grading curve from where the total fine aggregate content is determined. By establish a w/p-ratio/ λ_{25}-value diagram, see Figure 3-3, different types of concretes can be composed when the micro mortar phase is assembled with the aggregate skeleton depending on how the w/p-ratio and λ_{25}-values are combined.

This kind of classification of the micro mortar valid for the available materials is a helpful tool for a potential user to make decisions regarding workability, demands on w/p-ratio and robustness.

3.7 Choosing an appropriate aggregate composition

3.7.1 Introduction

Aggregate is the main constituent by volume in concrete. It can thus easily be understood that the aggregate will significantly affect the properties of the concrete. It is a natural rounded material or produced by crushing rock, comprising a wide spectrum of properties depending on its mineral composition, particle shape and surface texture. All these properties add to the complexity of making concrete. In addition, it is also a relatively low-cost and strong concrete making material in comparison to other concrete making materials, e.g. cement and mineral additives. Optimizing the use of aggregates in concrete will gain concrete production in a lot of aspects; mainly economical but also hardening, strength and durability properties are affected by the aggregate skeleton.

According to Betonghandboken (1997) the most important aggregate properties for concrete mix-design are the gradation curve, filler content, mud content, maximum aggregate size and grain shape. In addition, each particle shape, mineral type and surface texture will affect the concrete properties.

An aggregate grading curve is a combination of sizes from the available materials. They should be mixed in such a way that the resulting concrete gets the desired properties. These properties should satisfy both the special requirements for SCC and the normal requirements for the structure that is to be erected. One grading curve that is ideal in all cases and for all types of material does probably not exist.

In appended paper B, "A Method for practical aggregate optimization aimed for self-compacting concrete mix-design", a method for how it can be possible to choose an appropriate aggregate grading curve regarding the properties of the available material is suggested. The main objective with the work presented in paper B is to investigate how aggregate optimization can be performed practically for use in self-compacting concrete.

The aggregate properties have been characterized regarding its degree of packing, its flow properties together with the calculated fineness modulus. These three parameters are believed to give relevant information on the usefulness of the aggregates and the test methods are chosen based on their simplicity to procure and use.

3.7.2 Results from performed tests

In paper B three known experimentally based aggregate characterization methods have been tested and evaluated; degree of packing, V-funnel flow time and the calculated fineness modulus.

Paper B includes an investigation of the correlation between the chosen test methods and how they can be combined to receive an appropriate aggregate skeleton for concrete. The evaluated test results together with the calculated fineness modulus have shown some significant relations, and some main tendencies can be concluded from the laboratory tests performed in paper B:

- The degree of packing, for the tests performed in paper B, is mainly a function of the fine aggregate content and high packing degree can be reached with different aggregate compositions. For a given fine aggregate content, there is a small decrease in the degree of packing while the coarser aggregate proportions are changed, i.e. 11-16mm is decreased and replaced by 4-8mm. For any given fine aggregate content, the highest degree of packing will be reached by a gap graded aggregate, which in this investigation means 0% 4-8mm.

- The V-funnel flow is mainly a function of the fine aggregate content where higher fine aggregate contents significantly improves the V-funnel flow, which also decreases the fineness modulus.
- The V-funnel flow is also a function of the proportions of the coarse aggregate. For a given fine aggregate content, every increase of the 4-8mm content will improve the V-funnel flow and an increase of the 11-16mm will decrease the V-funnel flow.
- High packing degree is partly related to a fast V-funnel flow.

3.7.3 Method for performance based aggregate optimization

When an aggregate grading curve is to be selected, it can be based on results from the three suggested characterization methods; degree of pacing, V-funnel flow and fineness modulus. However, it was concluded in paper B that similar degree of packing can be achieved from aggregate compositions with different fine aggregate contents. The suggestion to an interpretation of an aggregate test with the aim to choose an appropriate aggregate grading curve is based on:

- the fine aggregate content
- the demands on passing ability
- the properties of the paste to be used

The fine aggregate content:
From the results presented in paper B it have been concluded that the degree of packing is mainly a function of the fine aggregate content. High packing can be received with an interval of fine aggregate content. The size of this interval will probably vary depending on the aggregate type. The fine aggregate content in concrete will, in addition, highly influence the fresh concrete properties.

The first step in the suggested aggregate optimization method is thus to identify the Fine Aggregate high packing INterval, denoted hereafter as the FAIN-interval, see Figure 3-4. It is the interval of fine aggregate content where the highest degree of packing occurs.

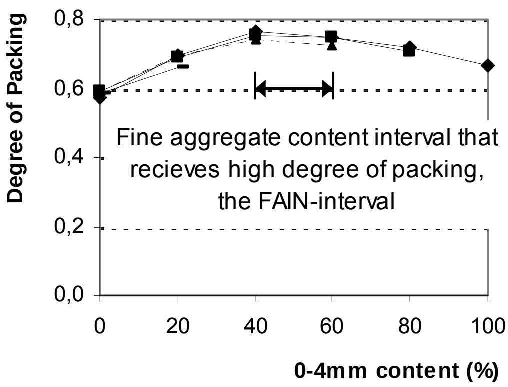


Figure 3-4 The fine aggregate interval where the highest degree of packing is received, denoted as the FAIN-interval.

The demands on passing ability:
The demands on passing ability are mainly based on the structural element to be cast and can thus vary between low or high demands. To manage high passing demands, it can performed by replace the coarse aggregate content with fine aggregate content or it can be performed by composing the coarse aggregates in a manner that facilitate the passing through narrow spaces. Depending on how the fine aggregate content is chosen within the FAIN-interval, the remaining coarse aggregate content will vary.

Low demands on passing ability: The fine aggregate content can be low within the FAIN-interval. If the concrete can manage the blocking criteria when paste is added, it might be an economical solution.

High demands on passing ability: The distance between the coarse aggregate particles can be increased by either a high fine aggregate content or a lower fine aggregate content together with increased paste content, or these two alternatives together. The interaction between the fine aggregate content and the paste content is discussed in the next section.

The coarse aggregate gradation can also be based on results using the V-funnel flow test. Higher V-funnel flow is an indication of lower inner particle friction between the aggregate particles. It has been concluded, based on the results presented in paper B, that higher V-funnel flow can be achieved when the coarsest particles are decreased.

The properties of the paste to be used:
The relation between the paste properties and the fine aggregate content is often mentioned as an important parameter for the concrete deformability (Okamura and Ozawa, 1995). It can generally be said that higher fine aggregate content demands higher paste and water content in comparison to lower fine aggregate contents (Powers, 1932). Choosing an appropriate aggregate grading curve shall thus also include the properties of the cement paste aimed to be used.

In case of low water to powder ratio, the fine aggregate content can be chosen from the lower limit in the FAIN-interval, since lower w/p-ratio generally shall be combined with lower fine aggregate contents. However, it might happen that blocking or particle interference occurs. The fine aggregate content and the corresponding paste content must than be further increased to increase the distance between the coarse aggregate particles.

In case of relatively high water-to-powder ratio, the fine aggregate content can be chosen from the upper limit in the FAIN-interval, even if combined with moderate paste content, since higher w/p-ratio normally can comprise higher fine aggregate contents. It will automatically result in lower coarse aggregate content.

3.7.4 Concluding remarks from paper B

The results from paper B indicate that one single aggregate characterization method seldom is enough for a proper interpretation with respect to the influence from an aggregate grading curve on the fresh concrete properties. It has been concluded that the highest packing for both of the tested aggregate types will be obtained when the fine aggregate content is ranging from 40% to 60% of the total aggregate content. In a concrete mix, these two amounts will affect the concrete properties differently because of the close relation between fine aggregate content, paste content, water content and mortar workability.

A high packing degree is often declared to decrease the paste content needed for remained workability, since the voids to be filled with paste will decrease, e.g. Goltermann et al. (1997). However, the paste shall, in addition to fill the free voids, also enclose each aggregate particle. The aggregate surface area will thus highly influence the paste content needed. The fineness modulus is an indication of the surface area of an aggregate grading curve and the results from paper B have shown that equal high packing can be obtained for aggregate compositions with a relatively wide spread in fineness modulus. Choosing an aggregate grading curve only based on the highest degree of packing can be misleading since the particle surface area also highly influences the paste content needed. It is thus essential, when working with aggregate optimization, to know how to interpret the result properly to receive the most appropriate grading curve for a specific application.

3.8 Assembling to a concrete matrix

3.8.1 Introduction

When regarding concrete as two phases during the mix-design process, the assembling part is essential and the results received from each phase shall be reflected in the total concrete mix. Otherwise, the results from the optimization work in the different phases can not be interpreted correctly. According to earlier discussion, sufficient concrete workability is received in two steps, 1) an excess of paste in mortar or micro mortar, here expressed by the λ_{25} and 2) an excess of mortar or micro mortar in the concrete mix.

1) Micro mortar workability

The micro mortar is optimized regarding demands on water-to-cement ratio, type of HWRA, type of filler and also the content and type of the finest aggregate, i.e. 0-0.25mm, as described in section 3.6. The micro mortar optimization has received information about how the content of binder and mineral additives and the water to powder ratio shall be combined in relation to the A_{25} content (the λ_{25}-value) to receive adequate fluidity and robustness. If the quote is retained in the concrete matrix, the specific amounts of A_{25} or binder are free to vary. From the amount of the total fine aggregate content, 0-4mm, it is possible to calculate the total amount of particles ranging from 0 to 0.25mm. For any given fine aggregate content, the corresponding binder content can be calculated to receive the same λ_{25}-value as has been tested in the micro mortar optimization. The content of cement and mineral additives together with the water content, chosen with respect to the w/p-ratio, is creating the paste that shall fill the voids around the fine aggregate particles with the aim to receive sufficient micro mortar workability. This can be illustrated by Figure 3-5a. The fluidity of micro mortar for a given w/p-ratio will increase when the λ_{25}-value decreases. Yen et al. (2000)

found that when the paste layer thickness in mortar increased, the fluidity increased to a certain limit. Beyond that limit, the fluidity was not further improved by an addition of paste thickness. Analogous, for a given w/p-ratio, the fluidity of micro mortar is not further improved when the λ_{25}-value has reached a certain lower limit.

2) Concrete workability

The coarse aggregate in concrete are covered with a layer of mortar or micro mortar, i.e. the voids are overfilled. This layer must be sufficiently thick to fulfill the demands on filling and passing ability. It means that the volume of coarse aggregate in the total concrete mix will affect the layer thickness and the corresponding workability. Thus, even if sufficient micro mortar workability is received, it does not automatically receive sufficient concrete workability. This phenomenon has been described by Mørtsell et al. (1996) valid for the Particle-matrix model as: for low matrix volume, i.e. all particles smaller than 0.125mm, the particle properties, i.e. all particles larger than 0.125mm, will play a dominant role. At high matrix volumes, the properties of the matrix will dominate. The concrete workability, illustrated in Figure 3-5b, will probably show similar behaviour when micro mortar is added to a skeleton of coarse aggregate. At low contents of micro mortar, either blocking or particle interference will occur even if the micro mortar show sufficient workability by it self. When the micro mortar content increases, the coarse aggregate will be further separated and the concrete workability will be improved.

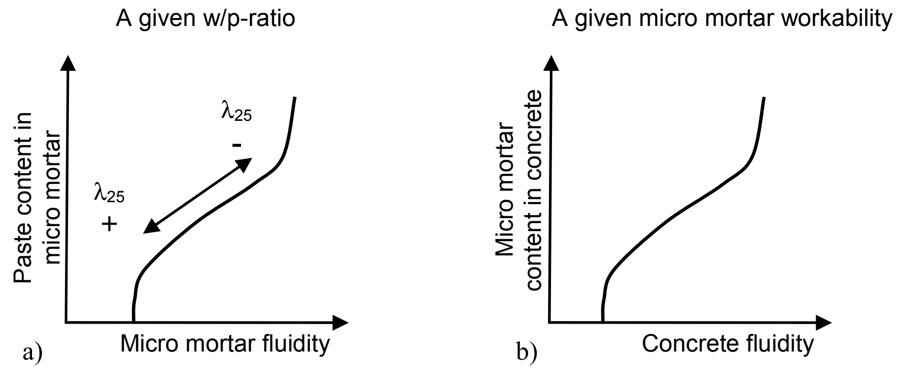


Figure 3-5 a) The workability of micro mortar due to the content of fine aggregate and corresponding paste, b) the concrete workability as a function of the micro mortar content.

3.8.2 Basic procedure for the suggested method

Figure 3-6 illustrates the basic assumption for the assembling process. A combination of aggregate comprises particles with sizes in the interval 0-0.25mm, A_{25}. The content of A_{25} in relation to the content of cement and mineral additives is the λ_{25}-value that shall be equal to the tested in the micro mortar optimization procedure, i.e. for a given fine aggregate content the corresponding binder and mineral additive content can be calculated.

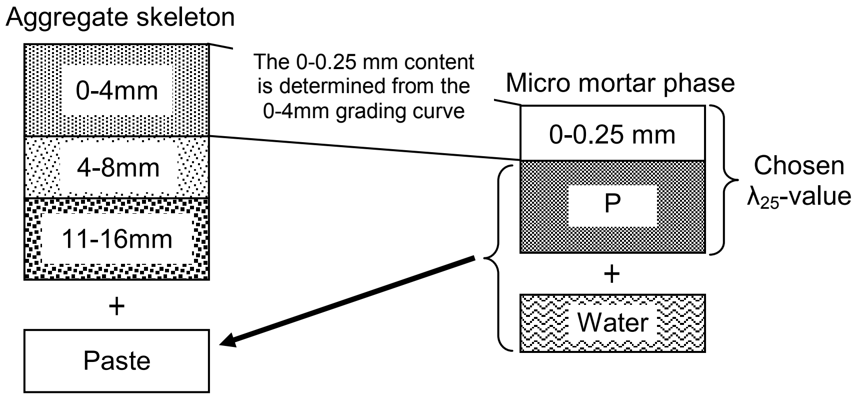


Figure 3-6 Illustration of the relation between the micro mortar phase and the aggregate phase.

The degree of excess cement paste in the fine aggregate are fulfilled because of the tested λ_{25}-value. Since the degree of excess micro mortar around the coarse aggregate shall be sufficient thick to receive demanded workability, the proposed assembling method might result in a paste thickness that is too small to receive sufficient workability classified as a self-compacting concrete when strictly applied. To perform the assembling part successfully, it is essential to understand how the paste, the fine aggregate content and the coarse aggregate content influence each other.

3.8.3 Fresh properties requirements

A well working SCC with sufficient properties shall fulfill three key properties; passing ability, filling ability, and resistance to segregation, see further in chapter 2. Depending on the application area and the structural performance, these three properties can be fulfilled in different ways.

The three main fresh property requirements shall always be fulfilled within the actual field of application. For practical purposes it means that the workability and its corresponding composition of the constituents can vary within a relatively wide area. If the materials are composed with respect to the structural performance it will probably increase the possibility to produce more cost effective concrete mixes.

3.8.4 Important parameters

It has been concluded from earlier researchers that there are three key parameters that are essential to succeed with a self-compacting concrete mix and its corresponding fresh properties; these are according to investigation performed by Domone (2006a):

- Paste content, with a mean value of 34% by volume
- Coarse aggregate content, with a mean value of 31% by volume
- Fine aggregate to mortar content, with a mean value of 47%

If referring to Powers, the most essential parameters for fresh concrete are:

- The quantity of the cement paste: i.e. the paste content

- The consistency of the paste, depending on the proportions and properties of the available materials: The consistency of the paste, including all small particles in concrete, is influenced of the sand content.
- The gradation and type of the aggregate: In case of high coarse aggregate content, the particle interference might be to high, which can be adjusted by increasing the paste content.

If one of the listed parameters increases or decreases, it will influence the others, which will result in changed concrete properties. To succeed with a concrete mix-design it is thus essential to understand these close relations and how each variation will affect the whole concrete mix and its corresponding properties, adjustments of the key parameters can thus be performed wisely.

3.8.4.1 The coarse aggregate content

When self-compacting concrete first was introduced in the middle of the 80[th] the mix-design approach was to limiting the coarse aggregate content and increasing the paste content. Limiting the coarse aggregate content means that the reduced content must be replaced by another material. This can be performed in two different ways as illustrated in Figure 3-7; either by increasing the paste content or by increasing the fine aggregate content. When the paste content or the fine aggregate content is increased also the fine aggregate to mortar quote will be affected, which also will influence the fresh concrete properties.

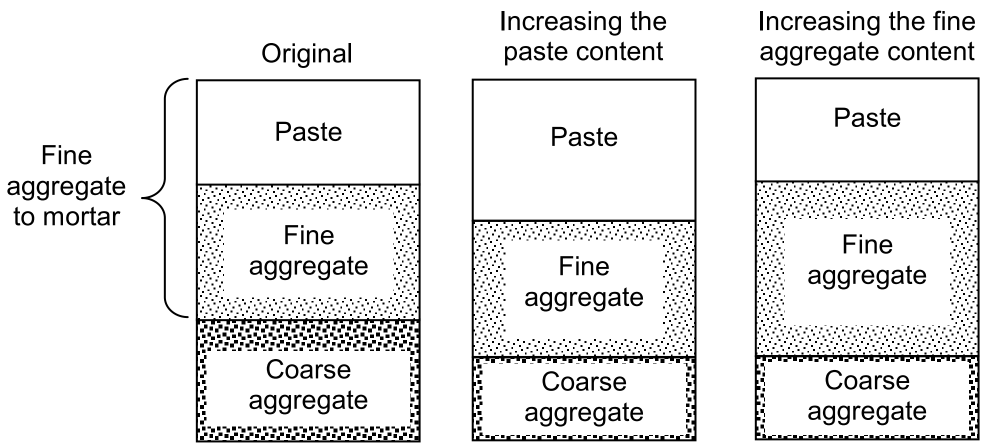


Figure 3-7 Illustration of how the volume of coarse aggregate content can be reduced by either increasing the paste content or by increasing the fine aggregate content by volume.

The coarse aggregate content is one of the most important key parameters when fulfilling the fresh properties requirements, and above all fulfilling the criteria for passing ability. In a situation with 60% fine aggregate content and normal SCC paste content, approximately 33-35%, the corresponding coarse aggregate content is ranging from around 22-27% by concrete volume depending on the cement paste content. Comparing these amounts with the coarse aggregate mean value of 31% by volume, it can be concluded that low coarse aggregate contents can be received even at relatively low paste contents. In such case, the particle interference might not be a critical part; the consistency of the micro mortar is thus probably the most essential property. In the case with 40% fine aggregate content, the corresponding coarse aggregate content will approximately be in the range of 34-43% by concrete volume depending on the degree of excess paste. In this case, the coarse aggregate content can be the critical part and higher paste contents might be needed to avoid particle interference and to fulfill demands on passing ability.

3.8.4.2 The paste content

If paste is added to an aggregate skeleton with a fixed grading curve, i.e. the mutual relation between the aggregate fractions is kept constant, the total aggregate content will decrease when the paste content increases. Assuming that the paste is increased, the paste content increase will thus result in a decrease of the fine aggregate content and its corresponding 0-0.25mm content, i.e. the A_{25} content, see Figure 3-8. This will result in two main changes in the whole concrete mix; 1) increased paste content, i.e. the coarser particles will be suspended and particle interference will be avoided, and 2) decreased λ_{25}-value, i.e. the fine aggregate particles will be suspended and the mortar workability is changed.

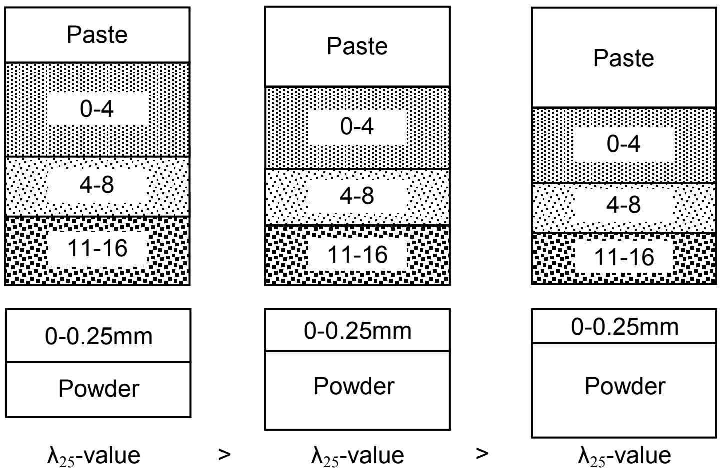


Figure 3-8 The volumetric effect of increasing the paste content and how the key parameters will change.

The paste content is strongly related to both the λ_{25}-value and the total aggregate content. It means that for each change in paste content with retained aggregate grading curve, also the λ_{25}-value and the coarse aggregate content will change.

When connecting the optimized micro mortar phase with the aggregate skeleton, the final paste content shall be sufficiently high to avoid particle interference and blocking of coarser particles. The amount chosen shall also be reflected in the tested and chosen λ_{25}-value to ensure sufficient deformability of the micro mortar.

3.8.4.3 The effect of paste, fine aggregate and the λ_{25}-value

The consistency of the cement paste is defined as one of the most important parameters influencing the concrete workability. Cement paste is defined as the sum of cement, water, mineral additives and superplastiziser. However, the cement paste consistency will be influenced by all particles in the same size interval as cement and mineral additives, e.g. the finest particles of the aggregate. The suggested λ_{25}-value, which can be evaluated experimentally, receives adequate information about how the total amount of cement and mineral additives shall be in proportion to the chosen fine aggregate for a given w/p-ratio to receive sufficient workability with the chosen superplastiziser. As the consistency of the paste is stated as a key parameter influencing the fresh concrete workability, it is essential that the chosen λ_{25}-value is reflected in the total concrete mix.

The fine aggregate to mortar quote is mentioned as an important parameter, Okamura and Ozawa (1995) suggest that it shall be fixed at 40%, and Domone (2006a) reports about 47%. In paper B the λ_{25}-value is evaluated valid for the available materials. The suggested λ_{25}-value is indirectly a similar parameter as the fine aggregate to mortar quote because it describes the proportions between the fine aggregate content and the paste content.

However, depending on the λ_{25}-value level, high, medium or low, it will highly influence other important parameters in the concrete mix. Assume that a relatively high λ_{25}-value has been chosen from the micro mortar tests, 0.50 could be regarded as high in performed tests in paper A. If a normal SCC paste content, approximately 35% by volume, is chosen, the fine aggregate content can be relatively high to receive a high λ_{25}-value. This will automatically result in a low coarse aggregate content, as illustrated in Figure 3-9. For this particular case, if the workability can be fulfilled due to the tested λ_{25}-value, the coarse aggregate content will be low because of the high fine aggregate content, which is favourable with respect to the blocking criteria.

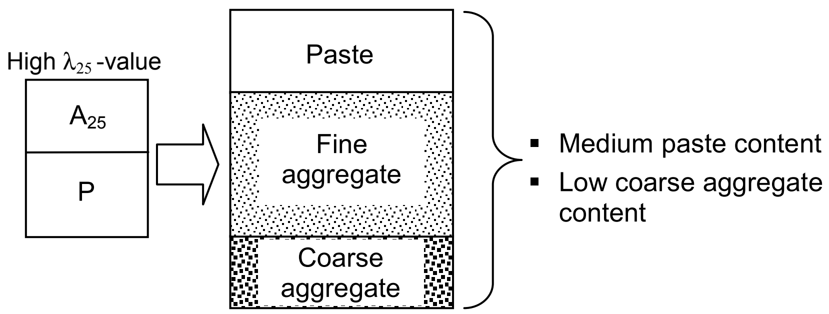


Figure 3-9 The effect on concrete mix-design when the λ_{25}-value is high.

Assume the opposite situation, a relatively low λ_{25}-value is chosen to receive sufficient micro mortar properties; 0.20 was one of the lowest in the performed tests in paper A. If a normal SCC paste content is chosen, the fine aggregate content must be relatively low to receive the low λ_{25}-value. This will result in a high coarse aggregate content, as illustrated in Figure 3-10 /alternative A. Even if the micro mortar shows sufficient workability, there might be a particle interference problem because of the high coarse aggregate content, as discussed by Powers (1932).

As an alternative, when the λ_{25}-value is low, is to choose a higher fine aggregate content that will result in a limited coarse aggregate content. However, the total paste content must then be increased to fulfill the demanded low λ_{25}-value, as illustrated in Figure 3-10 / alternative B.

When the λ_{25}-value is low or even very low, the paste content must probably be extremely high to ensure that the λ_{25}-value is fulfilled and to avoid particle interference.

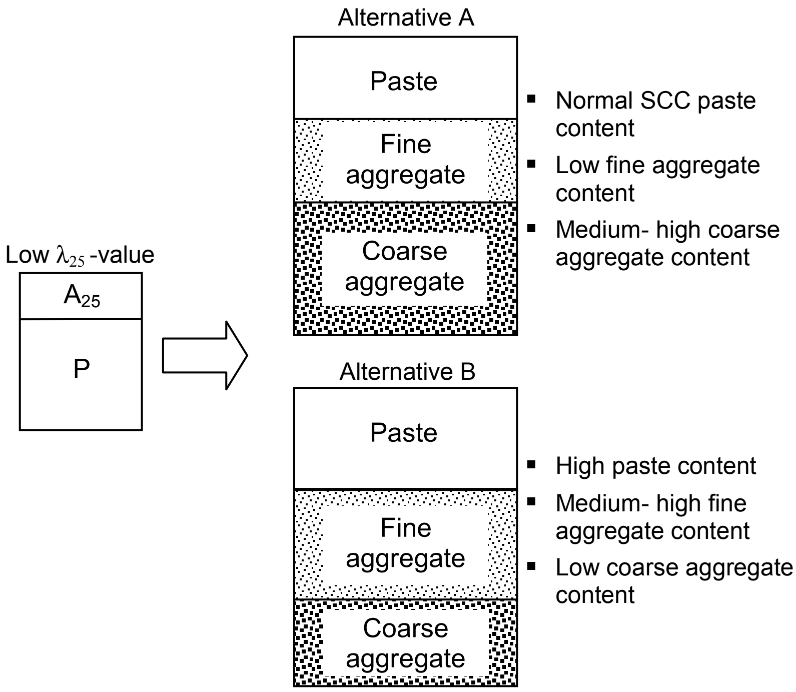


Figure 3-10 The effect on concrete mix-design when the λ_{25}-value is low.

3.8.5 Method for a the λ_{25} mix-design method

3.8.5.1 General

In the discussions in earlier sections, the complexity with concrete mix-design has been in focus. It has been concluded that there is a very close relation between the most important parameters affecting the fresh concrete properties; paste content, consistency of the paste, coarse aggregate content, the λ_{25}-value and the water to powder ratio.

When composing a concrete mix based on input from the two tested phases, micro mortar and aggregate, the constituents shall be combined in a way that fulfills demands on workability, economy and robustness for the chosen type of materials. Stated demands are probably different depending on type of application and a potential user shall be able to make decisions regarding workability, robustness and its corresponding cost.

3.8.5.2 Workability of micro mortar

The basis in SCC mix-design is the workability of the concrete, chosen regarding the structural element to be cast. Paste in combination with the fine aggregate is the key parameters influencing the workability, here expressed by the material related parameter λ_{25}. The experimentally chosen λ_{25}-value will ensure sufficient workability of the micro mortar based on the actual material, which allow a slightly variation of the λ_{25} for a given w/p-ratio. The λ_{25}-value and its corresponding w/p-ratio can be evaluated from an established λ_{25}-value/water to powder ratio diagram, see Figure 3-3.

The chosen degree of micro mortar workability will probably influence the degree of needed micro mortar content in the concrete mix. In case of higher λ_{25}, i.e. stiffer micro mortar mix, the degree of overfilled micro mortar in concrete shall probably be higher. Ouchi et al. (1999) reported, based on results fully presented in Nagamoto et al. (1997), that for a given V-funnel speed on concrete, higher mortar flow are needed for mortar containing higher fine aggregate content. It indicates that there is a close relation between micro mortar fluidity, concrete fluidity and also the fine aggregate content.

It can thus be suspected that the Marsh cone flow for higher λ_{25}-values must be higher than the flow for lower λ_{25}-values to receive similar concrete flow. However, it has been concluded that for a given w/p-ratio, mixes with higher λ_{25}-values show lower Marsh cone flow. For a given w/p-ratio, the workability of concrete will probably be improved by choosing the lower λ_{25}-limit in comparison to the higher. Similar workability might be received for the higher λ_{25}-limit of the total micro mortar content is increased. There is a potential in using the λ_{25}-value, for a given w/p-ratio, to adjust the workability to fit different types of applications.

However, λ_{25} is the relation between the chosen sand content and the total content of powder, valid for a w/p-ratio. Due to Kennedy (1940), the necessary excess of paste to achieve a certain degree of workability depends on the consistency of the paste itself and the surface area of the aggregates. When translating micro mortar to a concrete mix with retained λ_{25}-quote, the paste is experimentally adapted to the total sand content and type, which indirectly includes the excess of the paste on the fine aggregate. The total amount of paste needed in concrete, determined from the λ_{25}-value, will probably be a function of the blocking criteria in the first place.

Parameter studies regarding the relation between micro mortar workability for different λ_{25}-values and the corresponding concrete workability are not further investigated within the frame of this thesis, but it is an important development of the suggested method, see suggestions to future work in section 6.

3.8.5.3 Demand on passing ability and concrete workability

The workability of the total concrete mix is, in addition to the workability of the micro mortar, a function of the excess of micro mortar in the coarse aggregate skeleton. The excess of micro mortar is a function of the total paste content and can always be adjusted with retained λ_{25} if the fine aggregate content is also adjusted. The criterion is to ensure that particle interference or blocking does not occur. The passing ability is a common effect of the coarse aggregate, the fine aggregate content and the total paste content. The demanded passing ability is probably formulated due to the type of application.

When the aggregate is chosen with regard to the demands on passing ability together with the tested λ_{25}-value that ensure sufficient micro mortar workability, an initial concrete mix is composed. However, in some cases the demanded passing ability is not sufficiently fulfilled and the coarse aggregate particles must be further separated. In some cases, the passing ability might be fulfilled but particle interference occurs due to high coarse aggregate content. The micro mortar content must, in both cases, be further increased to an appropriate amount to ensure sufficient workability. A flowability/paste content graph can preferable be established, as suggested in Figure 3-11. It shall be pointed out that the paste content shall be chosen in a manner that the tested λ_{25}-value is fulfilled. The illustrated graph shows how an excess of paste will influence the workability of fresh concrete. The upper limit is defined as the paste content, above which the flow properties are not improved significantly by addition of paste.

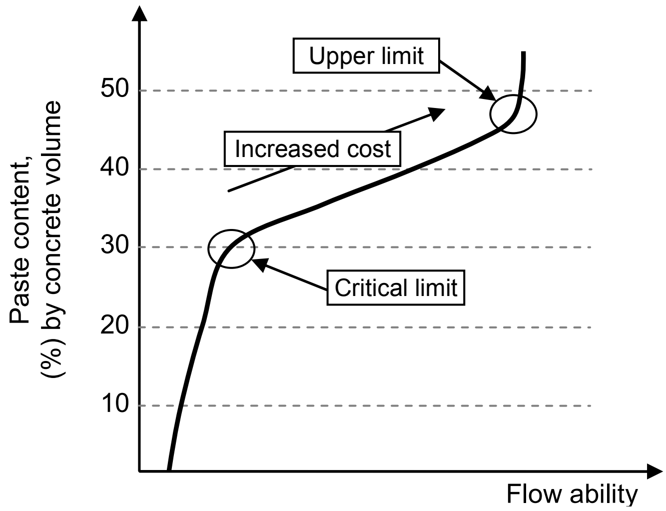


Figure 3-11 Illustration of the degree of excess paste and its contribution to the workability of concrete can be evaluated.

3.8.6 Working procedure for choosing a SCC mix based on micro mortar tests and aggregate optimization

The chain of connected parameters that together influences the total concrete mix and its corresponding workability has been discussed in the previous sections. A general working procedure will be suggested, which shall be seen as a tool to make decisions regarding; passing demands, λ_{25}-value, fine aggregate content, total paste content and the corresponding workability. The presented working procedure is based on some basic assumptions and definitions, which are as follows:

Basic assumptions:

- The initial filling ability is formulated by the chosen λ_{25}-value, which can be further adjusted if needed.
- The passing demands are fulfilled by adjusting, i.e. lowering, the volume content of coarse aggregate. It is performed by increasing the fine aggregate content and the corresponding paste content in a way that the initial λ_{25}-value is retained.
- The combination of materials, based on the tested key parameters, is initially based on a lean concrete alternative. When passing or filling ability is not fulfilled, the constituents are further adjusted.
- Adequate workability, passing ability and resistance to segregation can preferably be tested and evaluated with established practical workability test methods or with rheological tests.

Definitions:

- The definition of high and low λ_{25}-value is made on a qualitative basis because its absolute value is material related. The performed micro mortar tests within the frame of this thesis has shown that λ_{25}-values as high as 0.55 has been possible, and the lowest obtained limit has been approximately 0.15. Both of the values are related to w/p-ratio and the workability. λ_{25}-values below 0.30 will in the subsequence in this thesis be regarded as low and values higher than 0.30 will be regarded as high.
- As suggested in paper B, the fine aggregate content shall be chosen with respect to the degree of packing and also regarding the target λ_{25}-value. From packing tests, a FAIN-interval can be identified. The interval of fine aggregate content that receives the highest degree of packing can vary depending on material type, but dividing them into classes as described here can still be performed. The following definition is made for the fine aggregate content and it is illustrated in Figure 3-12:

  A= the lowest limit below the FAIN-interval

  B= the lowest limit in the FAIN-interval

  C= the middle of the FAIN-interval

  D= the upper limit in the FAIN-interval

  E= the highest limit above the FAIN-interval

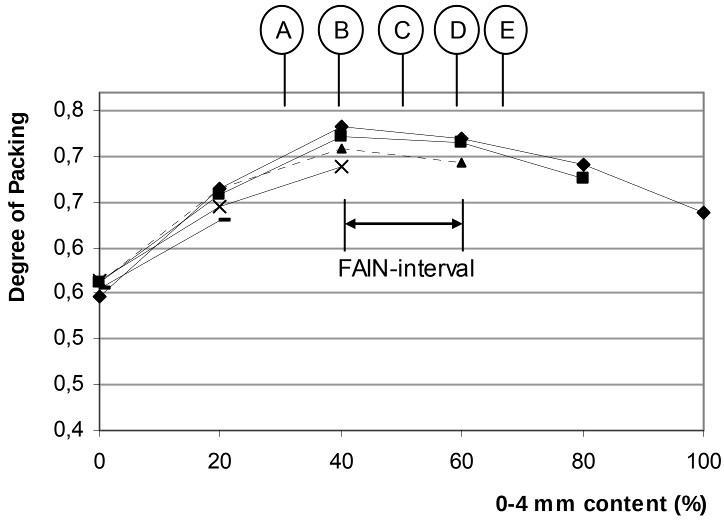


Figure 3-12 Definitions of the fine aggregate content, chosen due to the FAIN-interval.

The basic general method to receive a lean alternative:

When the λ_{25}-value is relatively high, a high fine aggregate content can be chosen, denoted as D. It will ensure a high λ_{25}-value even if a normal SCC paste content (approximately 35% by volume) is used. High fine aggregate content will automatically result in a decreased coarse aggregate content, approximately normal or lower than what has been reported as normal for SCC, i.e. approximately 31% by concrete volume. The critical part in this alternative is probably the filling ability, which can be improved by lowering the λ_{25}-value slightly.

In case of a low λ_{25}-value, a lower fine aggregate content must be chosen, the B alternative, to receive the low λ_{25}-value for normal SCC paste content, approximately 35% by volume. This will result in a coarse aggregate content that is relatively high for being a SCC, greater than about 31% by concrete volume. The critical part in this alternative will probably be the passing criteria, or that particle interference occurs. However, if the mix can manage the blocking criteria, this alternative is a lean solution because of the moderate paste content. However, in the case of blocking or particle interference, a possible solution is to increase the fine aggregate content and then also increase the paste content to fulfill the demanded low λ_{25}-value. The coarse aggregate will be further suspended because both the fine aggregate content and the paste content are increased.

Working procedure:

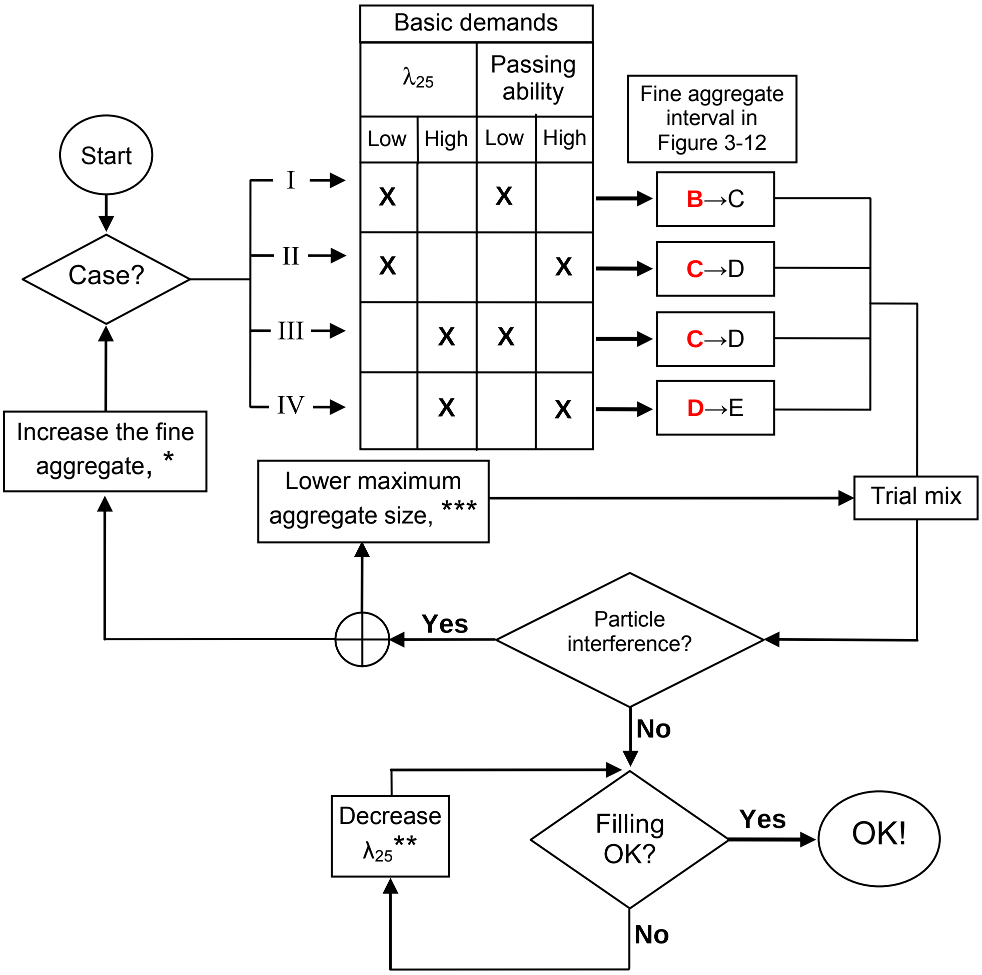
The suggested working procedure is illustrated by a flow chart in *Figure 3-13*. It is based on the described basic assumptions and the definitions regarding λ_{25} and fine aggregate content.

The work starts by identifying the present case regarding demands on passing ability and the level of λ_{25}-value. The fine aggregate content is chosen regarding demands on passing ability and the corresponding λ_{25}. The suggestion to an initial value of fine aggregate is marked red in Figure 3-13 and is decided with respect to the λ_{25} and is the lowest limit within its interval, see Figure 3-12.

By a chosen λ_{25}-value, choice of fine aggregate content according to Figure 3-13 and the demanded w/c-ratio the trial mix can be composed, which includes a calculation of the coarse aggregate.

In case of blocking or particle interference due to high coarse aggregate content, there are two possible solutions; 1) increase the fine aggregate content slightly, market with ⋆, with retained λ_{25}-value, i.e. the paste content is increased in accordance with the case in question denoted I, II, III and IV in Figure 3-13 or 2) lower the maximum aggregate size, market by ⋆⋆⋆ in the figure.

In case of the demands on blocking and particle interference are fulfilled, the filling ability is evaluated regarding the demands for the actual application. In the illustrated alternatives in Figure 3-13, the micro mortar workability is assumed to be fulfilled due to the experimentally tested λ_{25}-value and the concrete workability is fulfilled by increasing the total micro mortar content to a sufficient level. However, if the demands on passing ability are fulfilled but the filling ability is not sufficient and can not be further improved by adding superplastiziser, it is probably a situation where changes have to be made in the mix proportions of the constituents, market by ⋆⋆. Since workability of mortar is a function of the degree of excess paste in fine aggregate, the λ_{25}-value might be too high. Increasing the paste content with retained fine aggregate content improves the workability further. λ_{25} can be decreased in two ways; 1) by adding paste with retained fine aggregate content or 2) by decreasing the fine aggregate content with retained paste content. If the blocking criteria easily have been fulfilled, the latter alternative can preferable be used. If the blocking criteria precisely are fulfilled, the first alternative is the proper measure.



*) Increased fine aggregate content with retained λ_{25}-value

**) Lowering λ_{25} either by adding paste with retained fine aggregate content or by decreasing the fine aggregate content with retained paste content.

***) Increased micro mortar layer thickness for the suspension of the coarse aggregate, e.g. lowering the maximum aggregate size.

Figure 3-13 The suggested working procedure for varying levels of λ_{25} and corresponding fine aggregate content.

3.8.7 Possible limitations with λ_{25}

According the Powers (1932), higher sand content requires higher paste and water content. However, there is a lower limit, beyond which the particle interference between the coarse aggregates take place and lower sand contents will instead demand higher paste contents.

Similar behaviour might occur when cement paste is added to fine aggregates. As in the case with a combined aggregate curve, also fine aggregates comprise particles in different sizes. It has been discussed that fine aggregates with higher 0-0.25mm content probably demands higher paste and water content. However, as in the case with concrete, there is probably a lower limit beyond which particle interference between the coarser fine aggregate particles occur, and the fine aggregate might need even higher paste content. This lower limit is not further investigated here, but it shall be mentioned for further consideration. A possible solution might be to choose another upper limit in the micro mortar tests, e.g. 0.5mm, A_{50}.

3.9 Applications

3.9.1 Application 1

The risk for early thermal cracking of concrete containing fly ash is investigated in appended paper D. The fly ash content in the tested mixes is; 0%, 11% and 25%. These mixes have been composed by a strict usage of the λ_{25} mix-design method proposed in chapter 3. The most appropriate λ_{25}-value is chosen with respect to the binder contained, either 11% fly ash or 25% fly ash, with a demanded equivalent water-to-cement ratio of 0.40. The main objective with the composed mixes is to test the suggested λ_{25} mix-design method and compose mixes for the tests in paper D.

3.9.1.1 Materials

Table 3-1 Prescribed materials for the three mixes.

Cement	Anläggningscement CEM I 42,5, Cementa AB
Fly ash	Black coal fly ash from Rostok, Poland, produced by Warnow-Füller. Fulfill demands according to SS-EN 450 and is allowed for concrete production according to demands stated by SS-EN 206.
Aggregate	0-4mm, crushed aggregate, Uddevalla Sweden 4-8mm, crushed aggregate, Uddevalla Sweden 11-16mm, crushed aggregate, Uddevalla Sweden
Superplastisizer	Sikament 56, Sika AB
Air entraining agent	Sika AER, Sika AB

3.9.1.2 Stated demands

- Composed strictly due to the suggested λ_{25} mix-design method
- Equivalent water-to-cement ratio=0.40
- Cement content=400 kg/m^3
- Three fly ash contents; 0%, 11%, 25%, which are added in percent of the cement content

- Composing three mixes tol be used for the crack risk estimation tests, presented in paper D.

3.9.1.3 Choosing the micro mortar proportions

The micro mortar proportions are chosen due to results received from micro mortar tests performed according to the method presented in paper A. Decisions are made with respect to the demanded fly ash content; 0%, 11% and 25%, the demanded w_0/C_{equ}=0.40 and also that the cement content shall retain the same for all the three mixes. Figure 3-14 shows the micro mortar test results for compositions containing 11% and 25% fly ash, respectively.

When using 11% fly ash (% of the cement content), the total paste content will be relatively low for being a SCC mix. It was thus decided to take advantage from the fine aggregate as a part of the filler material. The micro mortar composition for the case with 11% fly ash was then chosen with respect to the highest possible λ_{25}-value that received a workable micro mortar, even if it was the stiffest λ_{25}-level for w/p-ratio 0.37. For this particular case, λ_{25}=0.55 was chosen, which is the highest possible λ_{25}-value for w/p-ratio 0.37 when fly ash is used. In a concrete mix, it means that the fine aggregate content can be relatively high.

In the case with 25% fly ash, λ_{25}=0.38 and λ_{25}=0.45 showed faster fluidity than λ_{25}=0.55. In addition, λ_{25}=0.38 showed longer buffering zone than λ_{25}=0.45, which in paper A is defined as more robust. λ_{25}=0.38 was thus chosen for the case with 25% fly ash content.

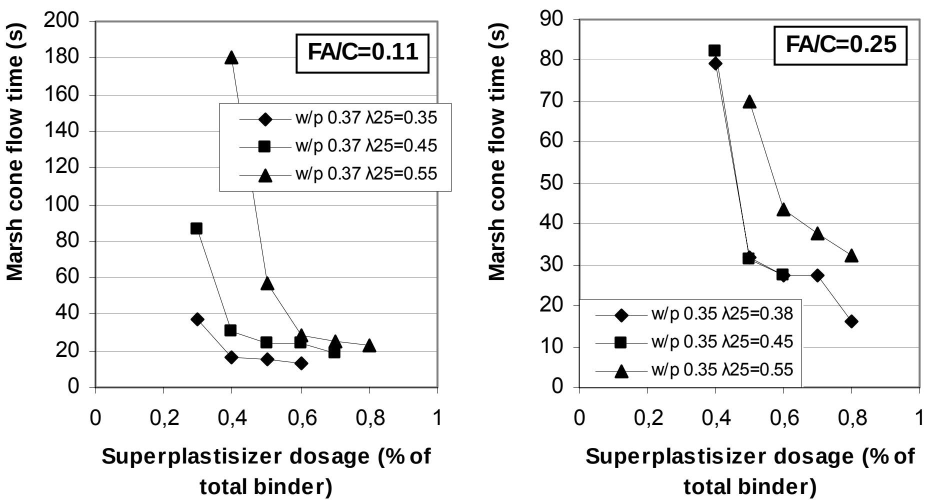


Figure 3-14 Results from the micro mortar test. Left figure is valid for 11% fly ash and w/p-ratio 0.37 and right figure is valid for 25% fly ash and w/p-ratio 0.35. Both mixes have an equivalent w/c-ratio that is 0.4.

3.9.1.4 Choosing the aggregate skeleton

In the case with 0% fly ash, dense packing, i.e. least void content, was used as the determining factor when choosing the aggregate grading curve, which also corresponds to a high fineness modulus. For concrete containing fly ash, the fine aggregate content is chosen within the FAIN-interval to match the tested λ_{25}-value, which is illustrated in Figure 3-15. In the case with 11% fly ash with a chosen λ_{25}-value of 0.55, the fine aggregate content is chosen to 63% of the total aggregate content and in the case with 25% fly ash, the fine aggregate content is chosen to be 53% of the total aggregate content.

The coarse aggregate gradation is chosen with respect to a low V-funnel flow in combination with a relatively high fineness modulus to ensure a moderate water demand.

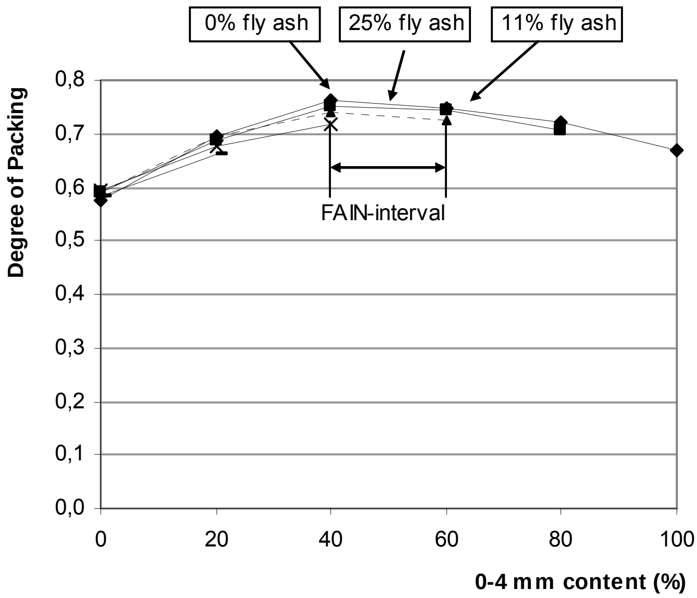


Figure 3-15 The degree of packing plotted versus the fine aggregate content for the used material. The FAIN-interval is identified as 40% to 60% of the total aggregate content.

3.9.1.5 Results

The final mix-composition for the three mixes is presented in Table 3-2. The λ_{25}-values for concrete containing fly ash have been slightly adjusted to receive the demanded equivalent w/c-ratio. It shall also be pointed out that the 0% fly ash mix is of a normal vibrated type, as not any type of mineral additive is added to the concrete.

Table 3-2 Mix composition for the three mixes

No.	w_0/C_{equ}	Fly ash content % of cement content	w_0/P	Paste content, % by concrete volume	λ_{25}	Fine aggre-gate, % of total aggregate	Coarse aggregate, % of total aggregate	Slump flow, mm
1	0.4	0	0.40	30.4	0.33	40	60	-
2	0.4	11	0.37	32.8	0.53	63	37	610
3	0.4	25	0.35	36.1	0.36	52	48	630

The mixes are only evaluated by slump flow and visual inspections. For the tested SCC mixes, No. 2 and No. 3, both show sufficient self-compacting properties even if the slump flow is relatively low (610mm and 630mm). The results confirm that the λ_{25} method is a fruitful way of creating SCC mixes. It has also been seen that it is possible to use the fine aggregate content as filler material when the paste content is low, as in the case with 11% fly ash.

Both objectives, confirm the λ_{25} method as a SCC mix-design tool and compose three mixes where two are of SCC type, were directly fulfilled without additional adjustments of the mix proportions. However, for other types of demanded workability, the tested mixes might be slightly adjusted.

In the case with 11% fly ash: the workability can be further improved by 1) increase the micro mortar content with retained λ_{25}-value or 2) by lowering the λ_{25}-value. To fulfil the first alternative, the fine aggregate content must be further increased. Since the initial fine aggregate content is outside the FAIN-interval, adjustment 2 might be the best alternative.

For 25% fly ash, the workability can be further improved by the same two types of adjustments as suggested for 11% fly ash. In this case, the fine aggregate content can be further increased with retained λ_{25}-value because its initial value is in the middle of the FAIN-interval.

Since the coarse aggregate content is relatively low, a third possible adjustment can be performed for both of the cases, and it is to create a gap graded aggregate gradation by excluding fraction 4-8mm and replace it with 11-16mm content. This will lower the fineness modulus, which may decrease the water demand slightly.

3.9.2 Application 2

A self-compacting concrete mix aimed for an indoor casting environment in a pre-fabrication industry was developed. The suggested concrete shall be used casting slabs with varying sizes, approximately 6m^2, and concrete will be manufactured continuously during the day on a daily basis.

3.9.2.1 Stated demands

A few, but essential, demands were stated:

- Robust mix; the mix shall be repeatable from time to time with retained properties.
- At least 20MPa compressive strength after 15 hours
- At least 30 minutes opening time
- Indoor casting
- No narrow sections or tight reinforcement in the formwork
- No demands on air content
- No economical frame; robustness is the most important criterion.

3.9.2.2 Materials

To meet the demand on early compressive strength, SH Cement (Swedish abbreviation for rapid hardening) was chosen. w/c-ratio between 0.40 and 0.45 was expected to receive sufficient 28-day compressive strength. The prescribed materials are presented in Table 3-3. The only available material characterization was the aggregate grading curves.

Table 3-3 Prescribed materials for application 2.

Cement	SH Cement, Cementa AB
Aggregate	0-8mm natural fine aggregate 8-16mm natural coarse aggregate
Mineral additives	Limestone filler, Limus 40, Nordkalk AB
Superplastisizer	Sikament 56 produced by Sika AB

3.9.2.3 Working procedure and results

Tests were performed on concrete only and the flow properties were evaluated with a slump flow and visual inspection. Since the sand was a natural sand type and no micro mortar tests were performed on this particular aggregate type, a λ_{25}-value tested earlier with another natural type of sand was chosen as an initial value. The first mix was composed due to the assumed λ_{25}-value of 0.33 together with an initially chosen w/c-ratio, of 0.40. The other parameters were chosen regarding SCC mean-values; 35% paste content and sand/gravel-ratio 60/40. Superplastiziser was added until sufficient fluidity was received. The first four trial mixes and its corresponding slump flows are presented Table 3-4.

1: The first trial mix did not show any fluidity, not even at high dosages of superplastiziser. Further addition of superplastiziser separated the mix without any improvement of the fluidity.

2: The λ_{25}-value was decreased by adding filler, which also resulted in a decreased w/p-ratio. A slightly improvement of the mobility was observed. However, high dosages of superplastiziser were still needed but the fluidity could not be further improved.

3: The λ_{25}-value was further decreased by lowering the fine aggregate content, compensated by an increased coarse aggregate content. An improvement was noticed.

4: Equal λ_{25}-value and an increased w/c-ratio. The fluidity was improved.

Table 3-4 The first four trial mixes, λ_{25} decreased from 0.33-0.23

No.	w/c	w/p	Paste content % by concrete volume	λ_{25}	Fine aggregate % of total aggregate	Coarse aggregate % of total aggregate	Slump flow (mm)
1	0.4	0.34	35	0.33	60	40	300
2	0.4	0.3	36	0.28	60	40	365
3	0.4	0.3	36	0.23	50	50	400
4	0.45	0.3	36	0.24	50	50	510

From the first four trial mixes it was concluded that the fluidity was improved by lowering the λ_{25} and by an increased w/c-ratio. The w/c-ratio was increased by changing the proportions between cement and filler, i.e. the w/p-ratio was not changed. It was thus assumed that the mix was improved by decreased cement content, replaced by filler, i.e. changing the proportions between the fine materials. For the next set of trial mixes, the λ_{25}-value was further decreased and the w/c-ratio and cement and filler proportions were used similar to trial mix number 4. To lower the λ_{25} without a further increase of the paste content, the fine aggregate content was limited to only 40% of the total aggregate content. This resulted in 60% of coarse aggregate. The next three trial mixes and its slump flows are presented Table 3-5.

5: Even at relatively high coarse aggregate contents, the concrete flow was improved and it could be noticed that the mortar workability was significantly improved for lower dosages of superplastiziser compared to mix Nos. 1-4. It was now concluded that the demanded λ_{25} should not exceed 0.20. However, due to the high coarse aggregate content, particle interference was noticed.

6: To avoid particle interference, the fine aggregate content was increased, which resulted in decreased coarse aggregate content. To receive λ_{25}=0.20, also the paste content was increased. It was now noticed a significant improvement of the slump flow.

7: In the last step, the paste content was further increased with retained λ_{25}, i.e. the paste thickness was increased. The slump flow reached 700mm and this mix was chosen to be further investigated in half scale and full scale tests in the future.

Table 3-5 The next three trial mixes, paste content increases from 35% to 45% by concrete volume.

No.	w/c	w/p	Paste content % by concrete volume	λ_{25}	Fine aggregate % of total aggregate	Coarse aggregate % of total aggregate	Slump flow (mm)
5	0.45	0.3	35	0.20	40	60	530
6	0.45	0.3	40	0.20	50	50	595
7	0.45	0.3	45	0.20	60	40	700

The effect of increased paste content, which also increases the maximum paste thickness, is illustrated in Figure 3-16 for mixes Nos. 5-7. The critical limit to receive sufficient self-compacting properties is, for this particular case, approximately 40% paste by concrete volume. By increasing the paste content further to 45%, the slump flow was further improved to 700mm.

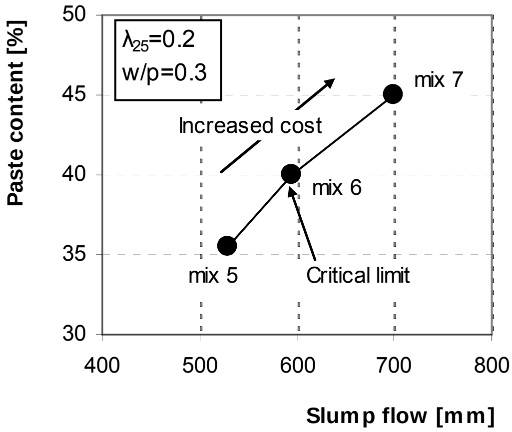


Figure 3-16 Paste content plotted versus the slump flow for mixes No. 5-7 in Table 4-4.

3.9.2.4 Concluding remarks to application 2

The mix-design work ended up in two mix alternatives, No. 6 and No. 7. Due to the lower paste content in No. 6, it is a less expensive alternative and due to the low demands on passing ability in this application, it is a well working alternative. However, mix No. 7 is a more robust alternative since it is not close to the critical limit and it was also seen that different dosages of superplastiziser could be added without significant changes of the fluidity. The client chose the last alternative, No. 7, since the benefit of having a very robust mix for this particular application was valued as a more cost-effective alternative on a long time perspective.

This application shows that λ_{25} can be used as a parameter for controlling and adjusting the workability of SCC even if a micro mortar test is not performed. It also shows how the total paste content, with constant λ_{25}, can be used to increase workability further, i.e. how an excess of mortar in coarse aggregate improves the workability.

3.9.3 Summary of the two applications

From the two applications, four different SCC mixes have been composed with varying properties. Regarding their λ_{25}-value and fine aggregate content, they can all be oriented to one of the four general groups suggested in the working procedure in section 3.8.5., which is illustrated in Figure 3-17.

The two mixes containing fly ash contain a relatively small amount of powder material, 444 kg/m^3 and 500 kg/m^3 respectively. These levels were chosen due to the demanded maximum cement content and its corresponding fly ash content, which is added in percent of the cement content. However, the results shows that SCC mixes can be composed with considerable lower powder contents than is "normal" for SCC if the w/p-ratio is properly combined with the type and amount of fine aggregate.

The results from application 2 have shown the possibility in making decisions regarding workability, benefit and cost. Since the application did not have any demands on passing ability, mix No. 6 could have been a less expensive alternative for this application. However, mix No. 7 showed a more robust behaviour, which was seen as the most important benefit in this case, the cost were thus of second priority. Cost-effectiveness was fulfilled by the robustness not by the price label.

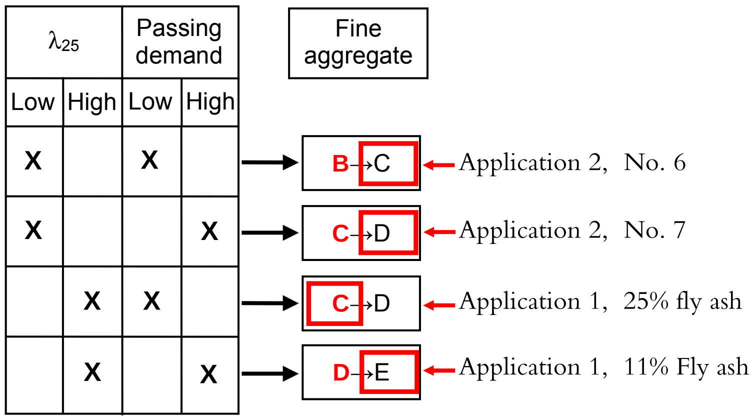


Figure 3-17 The tested mixes are oriented in one of the four general groups as suggested in the working procedure, see also Figure 3-15.

4 YOUNG CONCRETE PROPERTIES FOR CONCRETE CONTAINING FLY ASH

This section is a summary of appended papers C and D. They are briefly summarized due to the most important results, a complete description of the performed tests are presented in paper C and paper D.

4.1 General

Fly ash is a pozzolanic material, which means that it reacts with the calcium hydroxide $Ca(OH)_2$ that is produced when cement reacts with water. When fly ash reacts with $Ca(OH)_2$, calcium silicate hydrate (CSH) is formed, which means that the content of the durable material (CSH) increases in the concrete. Fly ash is often used in concrete because of its excellent concrete making properties, especially in the fresh phase. However, any incorporation of a pozzolanic material in concrete will influence the young and mature concrete properties. It is thus essential to understand how concrete properties will be influenced when fly ash is added to ensure the concrete performance (Papadakis et al., 1992 and Fraay et al., 1989).

4.2 Common approach for the fly ash evaluation

Fly ash in concrete is not common in Swedish concrete production, mainly because of the lack of national produced fly ash aimed for usage in concrete. However, there is an increased interest among concrete producers to use fly ash in concrete, either to replace some of the cement content or as a partial replacement of aggregate with the aim to increase the total paste content, which is one possible way of composing a self-compacting concrete.

The work presented in paper C and D was initiated with the aim to investigate the effect from fly ash on the young concrete behaviour when fly ash is combined with the Swedish cement type for civil engineering structures.

4.3 Heat and strength development on concrete containing fly ash

4.3.1 Introduction

The in-corporation of fly ash in concrete can be performed in three different ways, Berry and Malhotra, 1980):

1. Exchange cement with fly ash by weight on a 1:1 basis

2. Exchange parts of the cement and parts of the aggregate
3. Adding fly ash in addition to the cement as a part of the fine aggregate

According to Cannon (1968) fly ash contributes to the concrete strength in three different ways; by a water reduction because demanded workability can be received at lower water contents when fly ash is added, by an increased effective paste volume and by the pozzolanic reaction. The first two will influence the early concrete strength while the latter will contribute to increased long-term strength.

Any replacement of Portland cement with fly ash in concrete will influence the compressive strength, and the strength growth may be low in the beginning, but the growth usually continues up to at least 6 months (Berry and Malhotra, 1980). It is well known that in order to maintain the 28-days compressive strength the amount of fly ash added always exceeds the amount of cement removed (Cannon, 1968). This points out that the relation between fly ash and cement is one of the decisive parameters describing the strength growth

4.3.2 Aim and scope

The main objective with the work presented in paper C is to establish a numerical tendency model for heat development and strength growth in concrete containing fly ash in different amounts. Further, data from a tendency model shall be possible to use in structural analyses to be able assess effects of using variable fly ash contents for different structures at different conditions as a part of a production planning.

The heat development is tested with semi-adiabatic tests and the strength development is measured by compression tests on cubes cured in water at different temperature levels. Tests have been performed on concrete with two different water-to-cement ratios containing fly ash in three different amounts.

The tested mixes are composed with one type of fly ash, one type of aggregate, one type and dosage of superplastiziser as well as one type of cement with the aim to evaluate the pure effect from the fly ash content in combination with two levels of equivalent water-to-cement ratios. The tendency model is expected to reflect the combination of variable fly ash and variable water content.

4.3.3 Method

The tests have been performed due to the test program presented in paper C. For each value of w_0/C_{equ}, either 0.4 or 0.5, the water content and the equivalent cement content have retained constant.

The heat development has been determined on cylinder samples of concrete cured under semi-adiabatic conditions. After about two weeks the specimen has been heated, still situated inside the semi-adiabatic equipment, and the cooling phase has been registered. The exchange of heat with the surrounding during the hydration phase, expressed by the so called heat cooling ratio, is then possible to calculate.

The strength development in concrete is influenced by the temperature. Concrete cubes of 100·100·100mm have been stored in three different water temperatures: 5°, 20° and 35°, respectively. The concrete temperature is registered continuously and the strength development is studied by testing the compressive strength at four occasions between 8 and 168 h after casting. Additional cubes are cured under water in 20°C to determine the 28-day and 91-day compressive strength.

4.3.4 Conclusions

The following conclusions can be summarised from paper C:

- The presented numerical tendency model is a useful tool for estimating heat and strength development when fly ash is added in varying amounts. The model is based on the effect from w_0/C ratio and fly ash content in relation to cement content.
- According to the performed calculations, any replacement of cement with fly ash will significantly influence the young concrete properties. The effect on delayed strength growth increases with the increased amount of fly ash and will also increase for lower temperatures. In addition, the effect from fly ash increases at higher water-to-cement ratios.
- The suggested model is based on a test series where all parameters except the w_0/C ratios and fly ash content has been constant. It has been concluded that the suggested model can not directly be applied on concrete composed from other types of material. However, with a few additional tests and adjustments in the tendency model, it has been shown to be applicable on another concrete type with sufficient agreement.
- The suggested model is not a general numerical model valid for any type of concrete. To establish a more general model tests have to be performed studying all parameters that can effect the heat and strength development. For a given type of cement and a given type of fly ash, such additional parameters may be type and dosage of superplastiziser and aggregate type.

4.4 Estimation of the risk for early thermal cracking for SCC containing Fly ash

4.4.1 Introduction

Civil engineering structures are often massive constructions using concrete with high strength and low water to powder ratios. The combination of massive structures and high cement contents may cause undesired cracks during the hydration period. Civil engineering structures are often exposed to harsh environments with an expected service life of up to 100 years. Estimations of cracking risks during the hardening phase must thus be included in the design process in order to minimize the risk of durability problems in the future, such as corrosion risk of the reinforcement, water tightness and damages according to frost. The assessment for low crack risks includes decisions regarding necessary measures on the working site and also an evaluation of the mix composition and its heat and mechanical properties during hydration. Young concrete is here defined as concrete from casting and approximately the subsequent first month.

Hydration in concrete is an exothermic chemical reaction. A few hours after the concrete have been mixed the reaction between water and cement starts to generate heat. However, the concrete temperature rise is not uniform as the surface of the structure is affected by environmental conditions. A hardening concrete that is free to deform during the expansion and subsequent contraction phase during the hydration process will not be induced by stresses. But in practice, different parts of concrete structures are always restrained to varying levels of degree. The primary interest is whether or not these induced stresses will lead to cracking.

Estimation of the risk of early age cracking due to hydration requires knowledge of the hardening concrete. The risk for thermal cracking in young concrete is often interpreted regarding the stress or strain, where the risk for cracking is related to the tensile strength or the tensile failure strain. The stress and strain development in young concrete is, according to Emborg and Bernander (1994), mainly a function of four dominant factors:

Temperature development in the newly cast concrete: Is described by the heat of hydration and is mainly a function of the geometry of the structure, the cement type and content, and the environmental conditions.

The degree of restraint forces: Is defined as the possibility for the structure containing the newly cast concrete to deform during hydration.

The mechanical behaviour of the young concrete: The mechanical behaviour of young concrete that is of importance for the stress analysis are: strength development in varying temperature, the shrinkage, the thermal dilation, the viscoelastic behaviour and the non-linear stress-strain behaviour at high tensile stresses.

The temperature of adjoining structures: The size of the adjoining structure at time of casting of the new concrete is, for a structure free to deform, determined by its temperature. If the temperature of the adjoining structure is larger than the environmental temperature, it means, compared with a structure in temperature equilibrium with the environment, a reduction of cracking risks in the newly cast concrete.

In this paper properties of young concrete are tested and evaluated for concretes containing different amounts of fly ash. This covers necessary data to do crack risk analysis, and for some typical cases calculated crack risks are presented.

4.4.2 Aim and scope

The main objective with the work presented in paper D has been to investigate the effect from fly ash on the young concrete behaviour. Knowledge of the combined effect of temperature development and mechanical behaviour during the hydration period makes it possible to perform a stress analysis, and on this account the risk of thermal cracking can be estimated. The paper includes a comparison of the crack risk between concrete containing fly ash in different amounts with concrete without fly ash and with one earlier tested concrete containing limestone filler. This is done both directly from the tests as well as by analysis for some typical structural situations.

In the present investigation fly ash is added by a partial replacement of the aggregate; with the aim of increasing the total paste content as an action to produce a self-compacting concrete. This will result in an increase of the total binder content.

The tests have been evaluated in accordance with earlier established numerical models for further use in existing computer programs to realize crack risk analysis for arbitrary structural situations

4.4.3 Method

Theoretical and experimental methods with the purpose of mapping necessary young concrete properties to be able to realize calculations concerning risks of thermal as well as moisture induced stresses have been derived and evaluated at Luleå university of technology (LTU) during a long period (Emborg, 1989, Jonasson, 1994, Westman, 1999, Hedlund, 2000, Groth, 2000, Nilsson, 2003, Larson, 2003, and Carlswärd, 2006).

The tests performed in paper D are in accordance with an established "standard" procedure at LTU to map properties for usage in temperature and stress calculations. The most essential formulas are given in paper D.

4.4.4 Conclusions

- Established numerical models describing the properties of hardening concrete can be applied on concrete containing fly ash.
- The mixes containing fly ash and limestone filler had an increased early-age creep.
- The mixes containing fly ash had a higher heat development caused by increased binder content, as fly ash was added as replacement of part of the aggregate. However, a numerical stress analysis, for a typical situation in civil engineering construction, has shown that the risk for early age through cracks is significantly decreased for the mixes containing fly ash. In case of adding fly ash to concrete by a partial replacement of the cement, the crack risk will probably be further decreased. The positive effect from fly ash regarding the risk for through cracks could not be evaluated solely from the results from the temperature stress testing machine.
- The risk for surface cracks in the analyzed wall (0.7m) is very small for all of the evaluated mixes. Other dimensions have to be studied separately.
- The estimated risk for surface cracks in the analyzed slab (1m) on ground was not improved by an incorporation of fly ash. The mix containing 25% fly ash had the highest risk for surface cracks in the slab. It is probably an effect from the increased heat development in combination with the thickness of the slab. The increased heat development has probably compensated the positive effect from the increased early-age creep for concrete containing fly ash.
- The estimated risk for surface cracks in the slab for concrete containing limestone filler was significantly lower. It is probably a combined effect from moderate heat development and increased early-age creep.

5 SUMMARY AND MAIN CONCLUSIONS

5.1 Method for performance based self-compacting concrete mix-design.

Performance based concrete mix-design ranges a big area, which includes concrete properties in fresh, young and mature age. This thesis suggests how a performance based perspective can be applied on the fresh concrete properties.

The proposed mix-design method presents practical evaluating tools that make it possible to choose appropriate amounts of available materials to receive a suitable workability. The close relation between paste content, fine aggregate content and coarse aggregate content has been discussed, and composing SCC is a balance between demanded concrete workability and cost.

The most essential parts in the proposed mix-design method can be summarized as:

- Material related properties, which are of importance for fresh concrete, can be experimentally evaluated.
- The material properties are optimized in two phases; 1) micro mortar and 2) aggregate.
- The suggested optimization process is performed in a manner that facilitates the possibility to connect a micro mortar phase with a chosen aggregate grading curve. The key parameter λ_{25} has been introduced as the connecting parameter between the micro mortar and the fine aggregate.
- It has also been concluded that choosing an aggregate grading curve due to its degree of packing not give the best solution. The highest degree of packing is seldom reached for one unique aggregate composition; instead it can be reached for more than one aggregate grading curve.
- It is here suggested that aggregate packing tests shall be interpreted regarding the fine aggregate content, since the fine aggregate content highly influence the mortar workability. The FAIN-interval has been introduced, which is defined as the interval of fine aggregate where the highest degree of packing occurs. For the aggregates tested in this thesis, the FAIN-interval reaches between 40% and 60% fine aggregate content (0-4mm) of the total aggregate content (0-16mm).
- A structured procedure to compose a SCC mix based on the results from micro mortar tests and aggregate optimization tests is presented.
- The design procedure is initially based on a lean concrete alternative and adjustments to further improve the workability and the passing ability is suggested.

- The performed applications have shown the potential in making decisions regarding cost versus benefit.

5.2 The effect of fly ash on the young concrete properties

The following conclusions can be summarized from the work performed regarding the fly ash:

- The presented numerical tendency model is a useful tool for estimating heat and strength development when fly ash is added in varying amounts. The model is based on the effect from w_0/C ratio and fly ash content in relation to cement content.
- According to the performed calculations, replacement of cement with fly ash will in most situations delay the strength growth especially for lower temperatures.
- The mixes containing fly ash and limestone filler had an increased early-age creep.
- A numerical stress analysis, performed for a typical situation in civil engineering construction, has shown that the risk for early age through cracks is significantly decreased for the mixes containing fly ash.
- The estimated risk for surface cracks in the analyzed slab (1m) on ground was not improved by an incorporation of fly ash, which probably is an effect from the increased heat development in combination with the thickness of the slab.

6 SUGGESTIONS TO FURTHER WORK

6.1 Performance based concrete mix-design

The work performed in this thesis has shown that the suggested mix-design method is capable of composing well working SCC mixes based on experimentally determined properties for micro mortar and for the aggregate. However, there is still a lot of refining work left and possible limitations have to be further explored. Some suggestions to possible future research are here listed:

- The workability for SCC chosen with respect to a certain type of application has earlier been suggested by e.g. Walraven (2003). A further extension of the work presented here might be to formulate, based on the proposed mix-design method, a guideline that facilitates the possibility to reach a demanded workability formulated by the field of application.
- The relation between micro mortar fluidity, λ_{25}-value and the concrete workability must be further investigated.
- Study the influence on passing ability from different grading of the coarse aggregate, where the micro mortar workability and content are kept constant.
- An extended parameter study on how different types of fine aggregate influence the micro mortar properties and also the concrete properties.
- How micro mortar tests performed with different upper grain size limits influence the concrete properties when assembled to a concrete mix. It might be possible that other limits than the suggested, 0.25mm, will improve the correlation between micro mortar properties and the corresponding concrete properties.

6.2 Fly ash in concrete

Regarding concrete properties for mixes containing fly ash, there is a lot of work remaining for implementation in the Swedish concrete industry. It must be proven that the durability for a structure containing fly ash can be guaranteed. A direct continue from the work presented here might be:

- Study the effect on heat as well as on mechanical properties when concrete compositions are designed with respect to different applications. A model should be established for prediction of properties aimed for stress risk analyses.

- An extended investigation of the crack risk in early ages for concrete containing fly ash, which may include a deeper investigation to derive phenomena based on fundamental knowledge concerning chemistry and physics.

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Paper A

A Performance Based Experimental Micro Mortar Optimization Method for SCC

by Sofia Utsi and Jan-Erik Jonasson

A PERFORMANCE BASED EXPERIMENTAL MICRO MORTAR OPTIMIZATION METHOD FOR SCC

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Abstract

A self-compacting concrete (SCC) mix shall be well proportioned, robust and prove sufficient fluidity for the actual field of application and it shall, within reasonable economical frames, keep the consistency from the ready mix station until it has been placed in the formwork. It is thus essential to have reliable mix-design methods that facilitate the possibility to choose an appropriate combination of the available material regarding stated demands. Self-compacting mix-design can beneficially be seen as a two phase material, coarse aggregate in a matrix of mortar or an aggregate skeleton in a matrix of paste.

This paper is reporting about a systemized experimental micro mortar optimization method based on two simple tests, the mini slump test and the Marsh cone test, with the aim to characterize the flow properties regarding the effect of available materials and with respect to the actual type of application. In addition, the proposed method facilitates the connection between micro mortar optimization and the aggregate skeleton.

1 INTRODUCTION

1.1 Background

Self-compacting concrete (SCC) shall flow by its own weight, fill the formwork and enclose the reinforcement properly without any external vibration, and can be seen as one type of concrete within ”the concrete family”. SCC shall fulfill equal performance as normal vibrated concrete (NC) regarding the young and mature properties. The greatest differ between SCC and NC can be addressed to the fresh properties, where the demands on SCC are much higher and in addition, SCC is more sensitive to outer disturbance, i.e. less robust. There are two dominant factors that mainly affect the workability of SCC; 1) The flowability of mortar and 2) the volume fraction of coarse aggregates (Mørtsell et al., 1996, Okamura and Ouchi, 1999, Yen et al., 2000). The mortar (cement, water, mineral additives, superplastiziser and fine aggregate) shall carry and transport the coarse aggregate and in addition reduce the friction between the coarser aggregate particles so the concrete can fill the form and enclose the reinforcement properly, see for instance Okamura and Ozawa (1995), Okamura and Ozawa (1996) Okamura (1997). A robust and homogenous mortar with sufficient fluidity is thus essential for a successful SCC-mix. The properties of the mortar or the paste will above all affect the filling ability and the resistance to segregation, while the coarse aggregate content and its properties mainly affect the passing ability (Domone, 2006a).

A self-compacting concrete mix shall be composed to meet demands on fluidity, robustness and it shall, within reasonable economical frames, keep the consistency from the concrete plant until it has been placed in the formwork. SCC is a complex material and it can include a relatively wide range of properties regarding the fresh phase and it is relatively sensitive for outer disturbance such as external conditions and also regarding the properties of the chosen materials. It is thus essential to have reliable mix-design methods that facilitate the possibility to choose an appropriate combination of the available material regarding stated demands.

Fresh concrete can be regarded as solid particles suspended in water. However, depending on particle size, type and its influence on the concrete properties, it can for some reasons be simpler to regard concrete in different phases during the mix-design process, e.g. mortar or micro mortar. Optimizing the mortar separately to chose an appropriate combination of the smallest particles in concrete are often chosen as an experimental mix-design method because it might limit the amount of trial batches needed on concrete. Studying the paste or the mortar separately from the aggregate have been made by many other researchers, see for instance Okamura and Ozawa (1996), Billberg (1999), Agulló et al. (1999), Yen et al. (2000), Smeplass and Mørtsell (2001), Gettu et al. (2002), Hammer and Wallevik (2005), and Domone (2006a).

1.2 Practical method for experimental micro mortar optimization

The main objective with practical micro mortar tests aimed for concrete mix–design is to select appropriate combinations of the available material; cement, water, filler, superplastiziser and the fine aggregates. Type and amount of the constituents shall be valued and chosen regarding flow properties appropriate for the field of application and also regarding robustness. Micro mortar is here defined as all particles smaller than 0.25mm. A properly performed micro mortar test shall make it possible to interpret how different combinations of the available material, including the chosen superplastiziser, affect the fluidity and the robustness. In addition, the results shall be able to be translated into a concrete mix, i.e. micro mortar tests are of limited value if the results can not be translated to concrete.

The fluidity of cement paste or micro mortar can be described in terms of rheology as yield value and viscosity. Such classification is however based on the presence of a rheometer. The method proposed in this paper is developed based on a pragmatic perspective and is aimed to be an experimentally based micro mortar optimization method with the main focus held on material related properties for direct use in concrete production. Test methods are chosen regarding its simplicity to both procure and use because the suggested method shall be able to adopt without expensive laboratory equipments.

This paper is reporting about a systemized experimental based micro mortar optimization methodology based on the mini slump test and the Marsh cone test. The objective is to evaluate and characterize the flow properties regarding the effect of available materials and with respect to the actual type of application. The potential in receiving a relevant description of the fluidity of micro mortar by using a mini slump test together with the Marsh cone test have been reported earlier by e.g. Domone (2006a) and Agullo (1999), Gettu et al., (2002).

1.3 Scope and objective

Concrete can, experimentally, be regarded as coarse aggregates in a suspension of a viscous micro mortar, which means that the micro mortar can be composed separately to achieve sufficient properties for further use in a concrete. In general, the objective with micro mortar optimization is to investigate how the available materials shall be combined to achieve appropriate fluidity and robustness for the actual field of application.

The main object with the work presented in this paper is to develop a systemized methodology for practical micro mortar optimization. The micro mortar shall be optimized regarding its fluidity and regarding the available materials. In addition, the chosen proportions of the constituents and the corresponding flow properties shall be able to translate to a concrete matrix.

The suggested method is a systematic way of working with the smallest particles in the concrete mix, here defined as all particles smaller than 0.25mm, to obtain adequate information regarding the paste composition and its corresponding properties. It is based on simple test methods, the mini slump test and the Marsh cone test, and a structured method is suggested showing how the fluidity can be interpreted and characterized regarding available material. The work has been performed with the aim to facilitate the translation from micro mortar tests to a proposed concrete mix. The intended potential with the suggested method is that a potential user can interpret, from very simple test methods, different combinations of constituents regarding fluidity and robustness to form a basis for decisions regarding the optimal combination of the available materials.

Questions to be answered:

- What shall/can we measure with the Marsh cone and the mini slump test?
- How can the effect of the different constituents be evaluated?
- How can the fluidity of micro mortar be characterized with the mini slump flow and the Marsh cone test?
- How can we use the information to compose the most appropriate micro mortar mix for our application?

2 LABORATORY TESTS

2.1 Definition of key parameters

One principle to design a well working self-compacting concrete is known as using a large amount of fine materials, i.e. a large excess of cement paste. The paste provides fluidity and cohesion that can transport the coarse aggregates without segregation and is considered to largely affect the workability of the fresh concrete. It is thus of great importance that the paste is well combined and robust to meet these demands. The cement paste in SCC consists of cement, water, superplastisizer and mineral additives with an approximately grain size of 0-0.10 mm. However, also the fine aggregates consist of particles with grain sizes similar to the sizes of filler and cement. It can thus be assumed that the finest particles will influence the properties of the paste regarding the demands on water and superplastisizer and its corresponding fluidity. Paste test results performed only comprising cement, mineral admixture, water and superplastisizer can be difficult to translate properly to the concrete mix because of lack if information concerning the influence from the fine aggregate. It is thus more convenient to perform tests on micro mortar including all particles smaller than a chosen limit; water, cement, mineral admixture, finest part of the aggregate and superplastisizer. The finest particles in the chosen sand must be separated to perform the tests. For smaller particle size limits, larger amounts of sand must thus be handled and sieved, and for that reason the grain size limit is chosen to 0.25mm in the suggested test method. This limit has earlier been used by e.g. Billberg (1999).

When analyzing concrete in different phases during the mix-design process, it is essential that the phases are optimized and composed in a manner that the results from each phase are reflected in the total concrete matrix. Tests must be performed in such a way that the results can be interpreted regarding all particles, powder and fine aggregate, and the relation between them shall be translatable to absolute contents in concrete, i.e. when micro mortar and aggregate are mixed together.

Each type of fine aggregate contains an amount of particles smaller than 0.25mm, which can be evaluated from the grain size curve. For concrete mix-design purposes it means that the content of the fine aggregate in the concrete mix are in direct relationship with the amount of the finest aggregate particles in the micro mortar as illustrated in Figure 1. The absolute amount of fine aggregate will result in an absolute amount of aggregate particles ranges between 0 and 0.25mm, here denoted as A_{25}. The absolute content of cement and mineral additives is related to the total paste content in the concrete, which means that the proportions between powder and A_{25} are an effect of both the total paste content and the total fine aggregate content. If the fine aggregate content is increased or decreased, it will thus affect the properties of the micro mortar significantly.

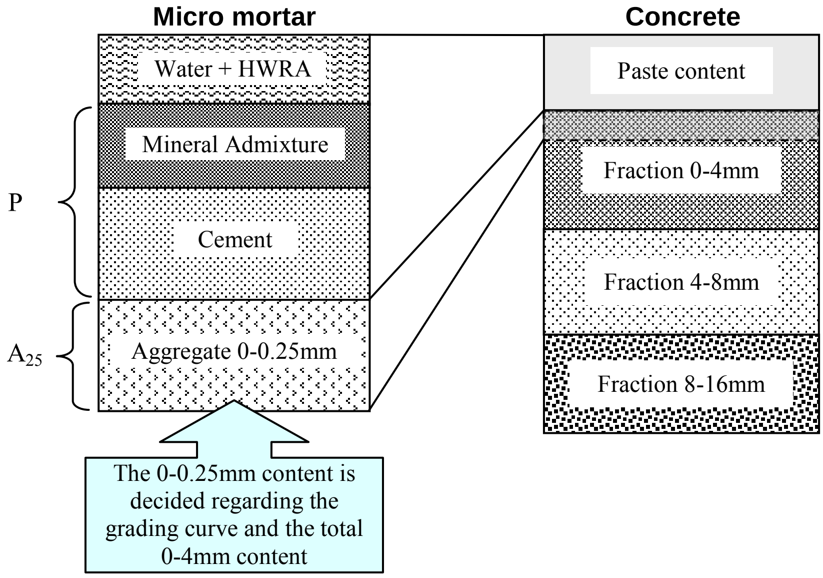

Figure 1 Schematic illustration of the relation between the concrete mix and the micro mortar phase.

To fully utilize the potential with micro mortar optimization it is desirable that the tests can be performed and interpreted independent from the absolute contents when used in concrete. In addition, the micro mortar tests shall be performed in such a way that the chosen combination of materials is reflected in the concrete, which will facilitate the connection between the micro mortar phase and the aggregate phase when assembled to a concrete mix. To fulfill these criterions we suggest the following parameter definition for micro mortar tests with the fine aggregate to powder quote, λ_{25}, described as:

$$\lambda_{25} = \frac{A_{25}}{P} \qquad \begin{aligned} A_{25} &= \text{Aggregate content of particles in the range } 0-0.25\text{mm} \\ P &= \text{Total content of powder} = \text{cement and mineral additives} \end{aligned}$$

The use of parameter λ_{25} increases the possibility to evaluate how the powders must be combined in relation to the finest aggregate content to achieve sufficient fluidity valid for the available aggregate type. In addition, the connection between the micro mortar tests and the chosen aggregate grading curve will be facilitated, and chosen proportions between the materials can be retained irrespectively from the absolute contents in the final concrete mix.

2.2 Characterization of micro mortar properties

A micro mortar test shall give adequate information about the fluidity and the robustness. The following properties are interpreted from the micro mortar tests:

Fluidity: The flow properties for varying combinations of materials are interpreted and characterized by a combination of the mini slump flow and the Marsh cone flow.

The effect from the superplastisizer: The main effect of superplastiziser is to disperse agglomerated particles in the cement paste (Aitcin et al. 1994). The agglomeration is a result of several types of interactions; Van der Waals interaction between particles, electrostatic interactions and interactions involving water molecules (Legrand and Wirquin, 1992). The effect of superplastiziser on the finest particles in concrete, i.e. the micro mortar, are here experimentally evaluated based on workability tests, here performed with a Marsh cone test together with a mini slump test.

The saturation point: The saturation point is defined by Aitcin et al. (1994) as the limit dosage of superplastiziser over which the superplastiziser is no more efficient and is determined as the flow time through a Marsh cone. Also Sedran (2000) and Gettu et al. (2002) are identifying this point in the Marsh cone test. The saturation point gives information about the superplastisizer dosage needed for different micro mortar compositions and its corresponding fluidity.

The buffering zone: The buffering zone can be defined as the interval of flow time beyond the saturation point, i.e. when superplastisizer is added but the flow time retains almost constant without segregation. A long buffering zone can be seen as an indication for robustness of the micro mortar, i.e. it is insensitive to variations in the superplastisizer dosage (Rodenstam, 2006).

Segregation: Resistance to segregation is one of the most important fresh properties for self-compacting concrete, it is thus essential to have reliable tools to determine if the tested mix is separated or not.

Point of segregation: The point of segregation is used as the definition when a mix is regarded as separated.

Robustness: A self-compacting mix that proves robustness means that it is insensitive against variations of its constituents. In addition, robustness also includes that the concrete keeps its consistency over time, i.e. shows limited workability losses during transportation and production.

2.3 Test method

2.3.1. General

A large set of micro mortar tests have been performed within the frame of the study in this paper. Different combinations of water-to-powder ratios and fine aggregate contents (λ_{25}-value) have been tested using the proposed test procedure.

The main objective with the performed tests has been to search for tendencies, logical connections and phenomena that occur for different combination of materials regarding the fluidity and robustness and mainly the effect from the fine aggregate content. By analyzing and structure the received information, it has been possible to suggest a systematic method for how micro mortar tests can be performed to make it possible to choose an appropriate combination of available materials regarding fluidity and robustness for further use in self-compacting concrete. The λ_{25}-value is suggested to be a key parameter for a direct connection to the fine aggregate content in concrete.

It shall be pointed out that this investigation is not intended to be a parameter study of different types of materials. Instead, it is a suggestion on how micro mortar can be optimized with two simple test methods for further use in concrete.

2.3.2. Material properties

Water-to-powder ratios from 0.27 to 0.37 have been included in the performed laboratory tests. Fly ash has been used as a mineral additive. Tests have been performed at different λ_{25}-values including one type of crushed fine aggregate with the maximum grain size 0.25mm. A natural type fine aggregate has been tested with the aim to clarify if the effect from type of aggregate can be interpreted with the two chosen test methods.

2.3.3. Mixing procedure

The mixes were prepared in a Hobart type mixer. The mixing sequences were as follows:

1. All dry materials (cement, mineral additives and the fine aggregate 0-0.25mm) were mixed for one minute.
2. The water and the superplastisizer were added and the mortar was mixed for another 5 minutes.

The test procedure was as follows; first the marsh cone with a 10mm nozzle was filled with micro mortar. The time needed for the sample to flow out of the cone was measured. Then the mini slump test was performed and the homogeneity of the micro mortar was evaluated regarding visual inspection and the scrap-test, defined in section 3.1.2.

2.3.4. Mini slump test

In the spread test, i.e. the mini slump flow, the final diameter for the paste or micro mortar is measured after self-weigh flow on a damped glass plate, see Figure 2. The test is based on the same principles as the slump flow for self-compacting concrete. The mini slump test is a simple test method giving information about how far a micro mortar can flow for a particular superplastisizer dosage. The sample is filled up in a slump cone and then lifted. The sample will flow out on the glass plate and the final diameter is measured.

Figure 2 Left figure shows the mini slump cone and right figure shows the final spread of a micro mortar in the mini slump test

2.3.5. Marsh cone test

The marsh cone test is a method to determine the time needed for a fixed volume of paste or micro mortar to pass through the cone, see Figure 3. The Marsh cone test is commonly used within the cement and petroleum industry to compare the fluidity of different grouts (Aitcin et al., 1994). A Marsh cone can be delivered with varying nozzle openings, which of course will generate different flow speeds. For the tests performed within the frame of this study, a nozzle opening of 10mm was used.

The prepared sample was poured into the damped cone up to a pre-defined level. The time needed for the sample to flow out of the cone was measured, which defines the Marsh cone flow time in seconds.

Figure 3 A Marsh cone. The time needed for the sample to flow out of the cone is measured.

3 RESULTS AND ANALYSIS OF PERFORMED MICRO MORTAR TESTS

3.1 Interpretation of test results

3.1.1. General

Results from the Marsh cone test and the corresponding mini slump flow show a typical behaviour, as illustrated in Figure 4. For low superplastisizer dosages, the Marsh cone flow time will decrease continuously when superplastiziser is added. For a certain dosage of superplastiziser, often very distinct, the flow time will not decrease further even if superplastisizer is added. This point is called the saturation point. When the superplastisizer dosage is further increased, the Marsh cone flow time is not further decreased beyond this point and superplastiziser can be added until the mix is separated. The interval of superplastiziser that can be added beyond the saturation point without any separation of the mix is called the buffering zone. Each Marsh cone flow corresponds to a mini slump flow. The mini slump flow will, unlike the insignificant reduction of the Marsh cone flow time, increase continuously when superplastisizer is added until the mix separates.

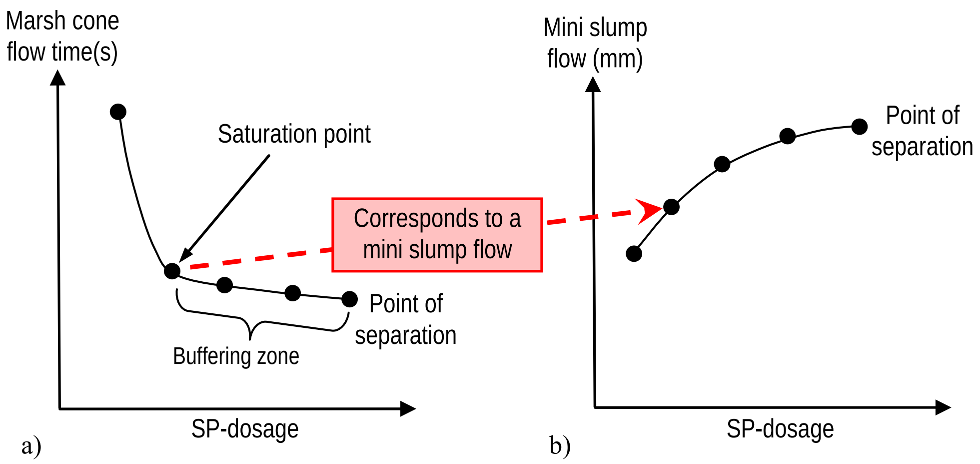

Figure 4 **Illustration of a typical behaviour when performing; a) the Marsh cone test and b) the mini slump flow. The saturation point can be interpreted and corresponds to a mini slump flow value.**

The flow behaviour in the Marsh cone test has been identified showing three general behaviours, here classified in three different groups; Type I, Type II and Type III, see Figure 5a). Type I starts to flow at the saturation point, and will then separate with only a small increase of the SP-dosage. Type II show similar behaviour in the beginning, it has a clear saturation point and in addition, the SP-dosage can be increased in further steps with retained fluidity and without segregation, i.e. a buffering zone exists. The third identified flow behaviour, Type III, increases its flow time while the

SP-dosage is increased and then separate at a certain level, it does not show a specific saturation point.

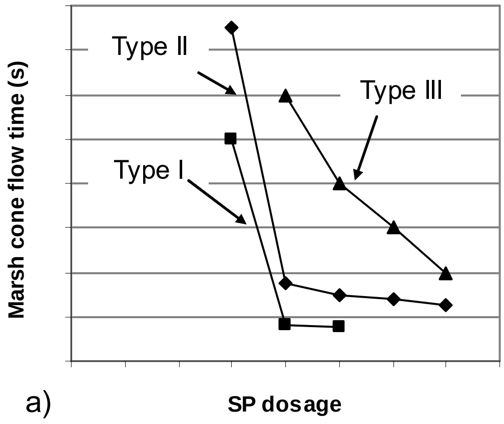

Figure 5 a) Three identified flow behaviours in the Marsh cone test and

The flow behaviour is important when interpreting and judging the test results. The Type II Marsh cone flow is preferable because it indicates that the mix is less sensitive to disturbance than Type I because of its longer buffering zone.

3.1.2. Evaluation of segregation

Resistance to segregation is essential for self-compacting concrete and is therefore stated as one of the principle functional requirements for fresh SCC (Skarendahl et al., 2006). Independent from the flow properties, self-compacting concrete shall always remain its homogeneity. In micro mortar tests, the main objective with interpreting the separation point is to make it possible to classify the fluidity and characterize the robustness.

The Marsh cone test does not generate a clear description about the condition regarding homogeneity; the behaviour through the funnel is similar just before and just after the mix is segregated.

The segregation can, in some cases, be interpreted by the mini slump spread, see Figure 6. The left curve shows a slight bend just before segregation. This behaviour will however not always occur, as illustrated by the right curve in Figure 5, which is a straight line all the way up to segregation. The point of segregation must probably be evaluated on a visual inspection basis.

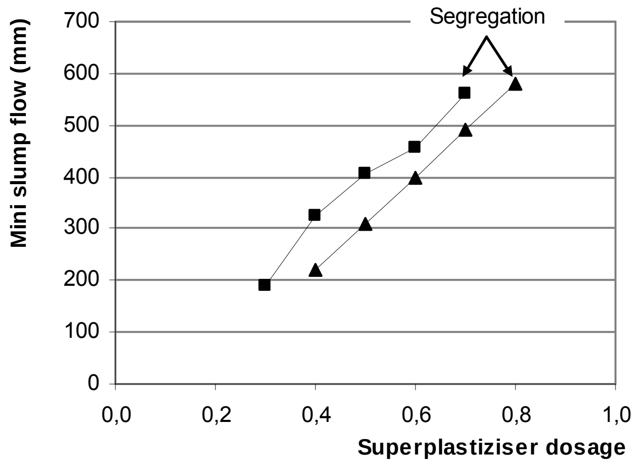

Figure 6 Two types of mini slump flow increase when superplastiziser is added.

When performing the mini slump test it is possible, on a visual inspection basis, to decide if a mix of micro mortar is segregated or not. It is here denoted as the scrap test. When a mini slump test is performed, the sample is floating out forming a circle on the test plate with varying diameter. The diameter itself does not tell anything about segregation; 500mm spread can be either homogenous or segregated. But, when the sample is scraped off the testing plate with a trowel it will be very obvious whether the micro mortar is segregated or not.

No segregation: The trowel can easily touch the plate and drive the paste or micro mortar off the testing plate without any resistance, see illustration in Figure 7a).

Half segregation: The paste can be driven off the plate but with a tendency of resistance because of particles that are stuck to the plate.

Segregated: The trowel can not touch the plate because the solid particles are totally stuck to the plate. The trowel can only drive the surface water of the plate, see illustration in Figure 7b).

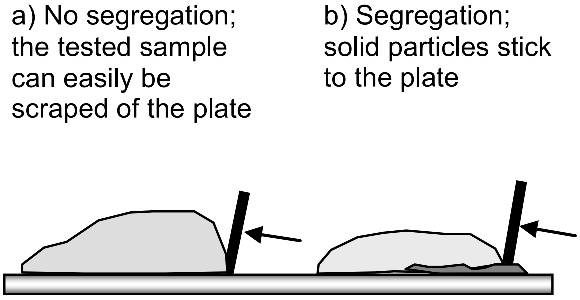

Figure 7 a) Scrap test showing a homogeny micro mortar mix. The scraper can easily touch the plate and drive the mix off the plate. b) A separated micro mortar. Solid particles stick to the plate and are impossible to scrap off.

3.1.3. Evaluation of the time-factor

A very important property regarding self-compacting concrete and its robustness is the possibility to keep its consistency for a period after mixing, above all when the transportation time is long. For practical purposes it means that the documented fresh properties at the concrete plant shall be retained when the concrete reach the working site. In Utsi (2003) it was concluded that the opening time for SCC is, above all, influenced by the chosen type of superplastisizer. Some types of superplastiziser will continue to increase the fluidity for a period after mixing, while other types will start to loose consistency almost immediately. For practical purposes it is important to choose an appropriate target value for the consistency for the newly mixed concrete in order to satisfy the expected consistence at working site. It can thus be wise to establish a general classification of how the consistency will change with time for the superplastiziser aimed to be used, as suggested in Figure 8. If the expected transportation time is known, the consistency at the concrete plant can be determined with such a diagram. When an appropriate micro mortar composition is chosen, the time/flow-relation can be tested to verify that the general tendency is valid for the chosen mix.

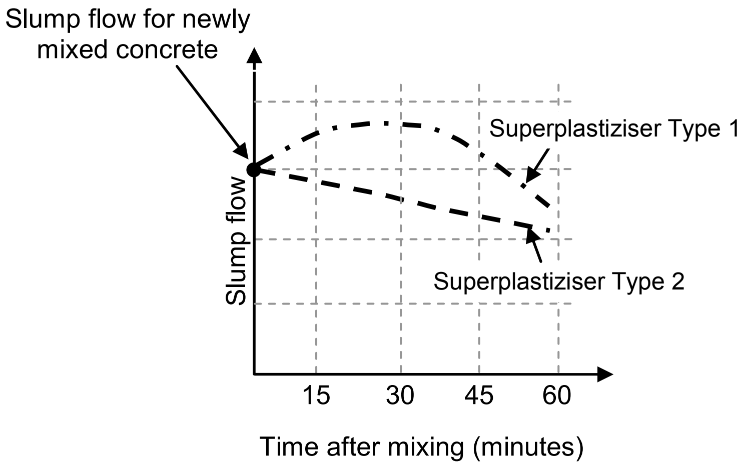

Figure 8 Suggestion to an established time/fluidity-diagram for different types of superplastiziser.

3.2 The effect of the constituents

3.2.1. Influence of the fine aggregate content

The influence of the fine aggregate content on the workability of fresh concrete was formulated by Kennedy (1940) when he introduced the "excess paste theory". Kennedy stated that for concrete to be workable, the volume of cement paste must be, as minimum, equal to the volume of the voids in the dry aggregate skeleton. For any degree of excess of cement paste, the workability will be improved. In addition, Kennedy also stated that for any required workability the amount of excess of cement paste depends on; 1) the consistency of the cement paste itself and 2) the surface area of the aggregates, larger surface area means that greater cement paste excess is required.

Yen et al. (2000) used Kennedy's paste thickness theory on fresh SCC and divided the theory in two steps, 1) an overfilled mortar, i.e. an excess of paste coating the fine aggregates and 2) an overfilled concrete, i.e. an excess of mortar coating the coarse aggregates. The coarse aggregates in self-compacting concrete are covered by a layer of mortar, sufficiently thick to give fluidity and passing ability. In addition, the fine aggregates in mortar shall be covered by a paste layer thick enough to achieve adequate mortar flow.

From the performed micro mortar tests, the influence of the finest aggregates can be interpreted regarding fluidity. By using the suggested key parameter λ_{25}, the effect of both the paste content and the properties of the actual fine aggregate type can experimentally be evaluated from the tests. When the λ_{25}-value is high it means that the powder content is relatively low in comparison to the fine aggregate content. As the λ_{25}-value decreases, the fine aggregate particles will be forced apart with the increased powder content, i.e. we have an increased paste layer thickness.

In Figure 9 the Marsh cone flow time is plotted against the dosage of superplastiziser for water-to-powder ratios 0.37 and 0.33. w/p-ratio 0.37 is tested with λ_{25}-values= 0.35, 0.45 and 0.55 and w/p-ratio 0.33 is tested for λ_{25}-values= 0.25, 0.35 and 0.45.

Some tendencies can be observed regarding the λ_{25}-value; a high λ_{25}-value needs a high superplastiziser dosage to achieve an adequate flow. The absolute Marsh cone flow time at the saturation point will increase when the λ_{25}-value increases and the effect from λ_{25} is higher for lower w/p-ratios. Similar phenomenon was showed by Yen et al. (2000), who concluded that for a constant w/p-ratio, the fluidity of mortar increased with the increase of the average paste coating thickness, i.e. lower proportions of fine aggregate.

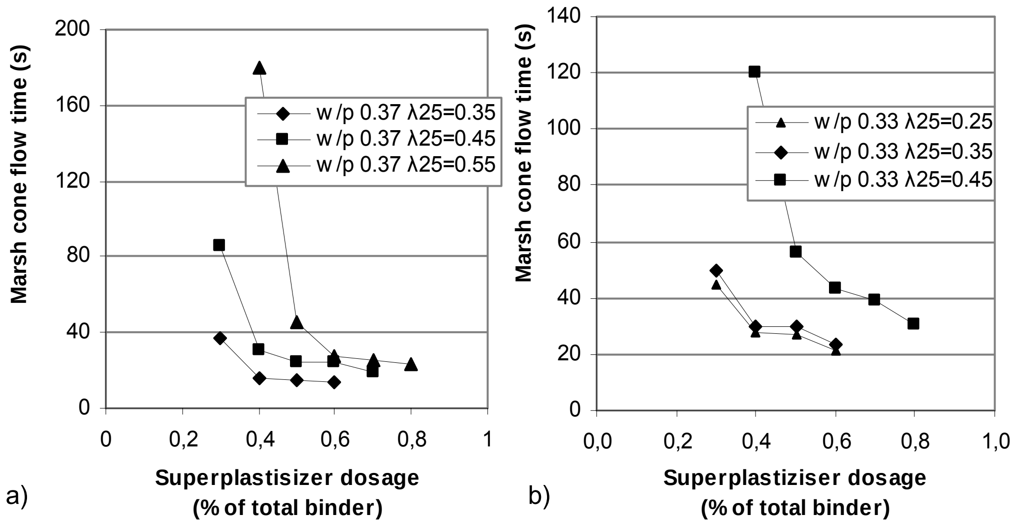

Figure 9 Marsh cone flow time plotted versus the superplastiziser dosage. a) w/p-ratio 0.37 and λ_{25}-values ranging from 0.35 to 0.55 and b) w/p-ratio 0.33 andλ_{25}-values ranging from 0.35 to 0.45.

In Figure 10 the mini slump flow is plotted against the corresponding Marsh cone flow time for mixes with w/p-ratio 0.37 and λ_{25}-values ranging from 0.35 to 0.55, and w/p-ratio 0.33 with λ_{25}-values ranging from 0.25 to 0.45. It can be seen in the figure that a mini slump flow over 400 mm can be achieved for all λ_{25}-values if the superplastisizer dosage is adjusted for each mix. The Marsh cone flow time is affected by the λ_{25}-value irrespectively from the dosage of superplastiziser where higher fine aggregate contents will result in slower speed through the funnel. It can thus be concluded that relatively high final mini slump flows can be achieved with adjustments of the superplastisizer but the Marsh cone flow time can not be improved beyond its saturation point and is a function of the mix-composition.

The mini slump flow can always be adjusted and increased by adding superplastisizer. It is however favourable to find sufficient fluidity as close to the saturation point as possible because it increases the distance to the point of separation. The mini slump flow that occurs at the saturation point in the figures above will slightly increase when the λ_{25}-value decreases. Higher mini slump flows can thus be achieved close to the saturation point for lower λ_{25}-values.

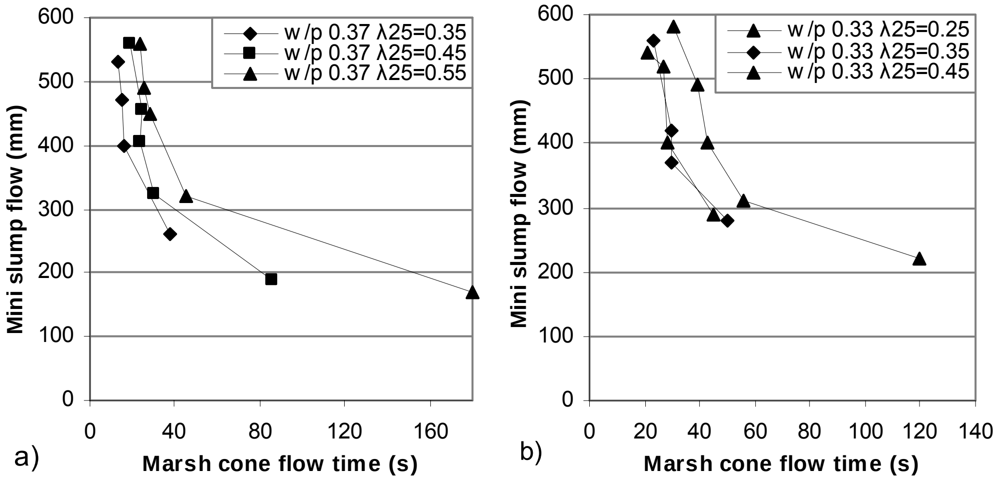

Figure 10 The mini slump flow plotted versus the Marsh cone flow time for; a) w/p-ratio 0.37 and λ_{25}-value 0.35, 0.45 and 0.55 and b) w/p-ratio 0.33 and λ_{25}-value 0.35 and 0.45.

In addition to the fine aggregate content, also type of aggregate significantly affects the properties of micro mortar. Two aggregates with similar grading curve can show significant difference in workability. It can be derived from surface texture, shape, porosity and mineralogy (Esping, 2007). Esping concluded that an increased surface, including filler and aggregates, significantly reduced the workability. It was also concluded that all mixes with higher surface area reached similar workability as the reference mix by an addition of extra water, which indicates that high surface area can be compensated by water. It was also discussed that the higher surface area can not be compensated by an addition of superplastiziser since these products mainly reduce the yield stress.

It can be observed in Figure 11 that different types of aggregates achieve varying fluidity. The fluidity of micro mortar mixes with natural aggregates and crushed aggregates are compared. The effect from type and amount of fine aggregate when combined with other chosen materials can be evaluated for further use in concrete. It can be observed that, for equal w/p-ratio and A_{25} content, the mixes with crushed aggregates can not reach as high Marsh cone flow as the natural type and it can be suspected that natural aggregate can be used in concrete with higher λ_{25}-value in comparison to crushed for equal w/p-ratio.

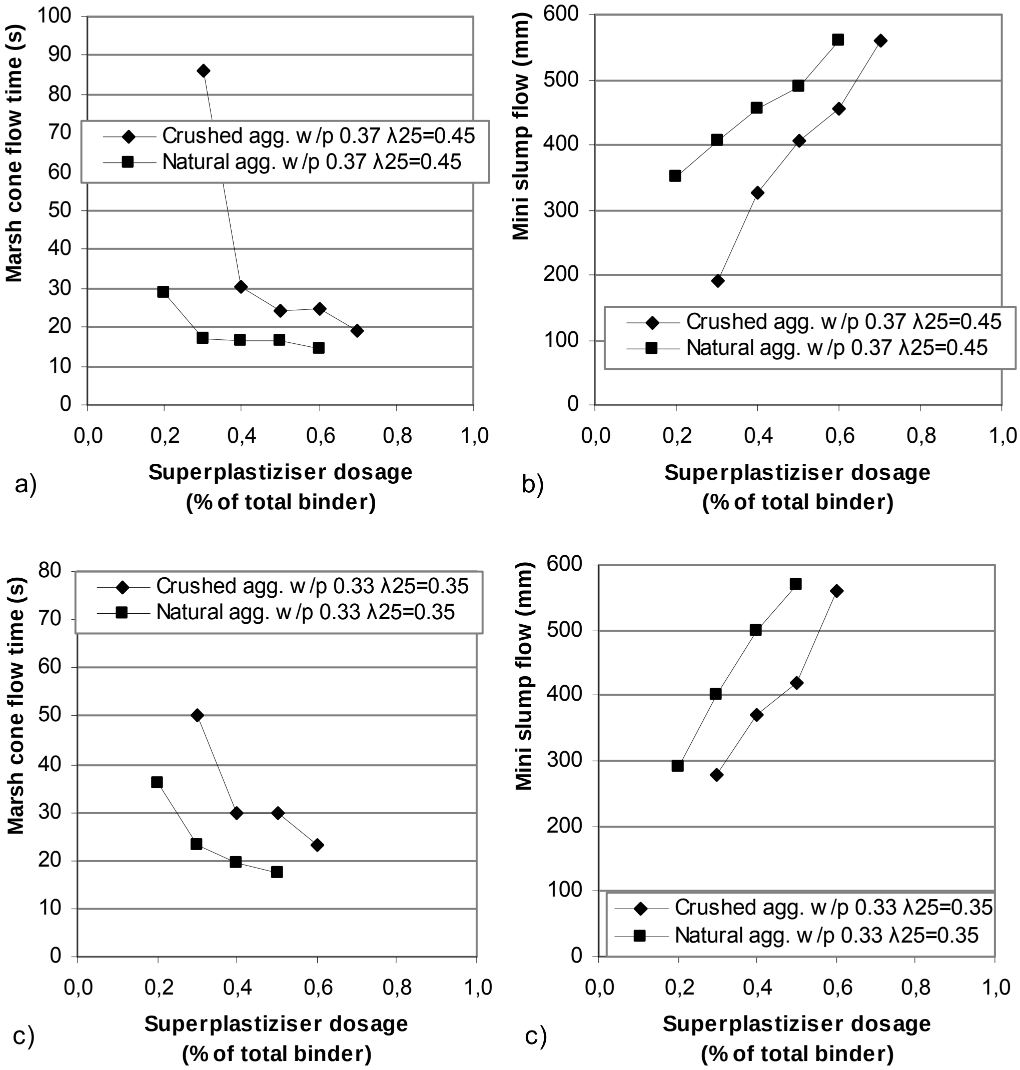

Figure 11 Results from the Marsh cone test and the mini slump test for crushed aggregates in comparison to natural aggregates.

3.2.2. Influence of the water-to-powder ratio

The water-to-powder ratio is a function of how viscous a concrete ia. The w/p-ratio effect can be interpreted from the Marsh cone test. In Figure 12a) the Marsh cone flow time is plotted versus the superplastisizer dosage for w/p-ratio 0.33 and 0.37 when the λ_{25}-value is fixed at 0.45. The results indicate that the Marsh cone flow time at the saturation point will increase for lower w/p-ratios. The corresponding mini slump flow is plotted in Figure 12b) where it can be seen; 1) the mini slump flow increases for each addition of the superplastisizer dosage, and 2) lower w/p-ratios need higher superplastiziser dosage for an adequate fluidity.

The close relation between increased Marsh cone flow time and decreased water-to-powder ratio has also been reported by Domone (2006a) who characterized the fluidity of mortar with the Marsh cone test and the mini slump test. Domone found that the water-to-powder ratio highly influences the Marsh cone flow time while the superplastiziser dosage influences the mini slump spread.

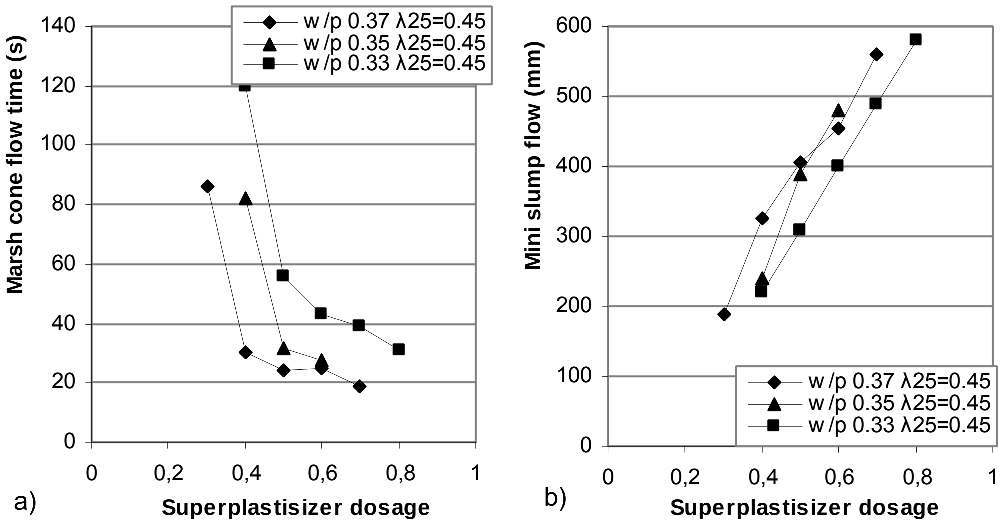

Figure 12 a) The Marsh cone flow time plotted versus the superplastisizer dosage for w/p-ratio 0.33 and 0.37 when the λ_{25}-value is 0.45. b) The corresponding mini slump flow for each superplastisizer dosage.

3.2.3. Cross effects of w/p-ratio and the corresponding λ_{25}-value

For a constant A_{25} content, the w/p-ratio will influence the Marsh cone flow time and also the superplastiziser dosage needed. In addition, also a cross effect between the w/p-ratio and the λ_{25}-value have been obtained. In Figure 13a) the λ_{25}-value is plotted against the Marsh cone flow time that occurs in the saturation point for w/p-ratio 0.37, 0.33 and 0.27.

When the w/p-ratio is 0.37 (high), the λ_{25}-value can range between approximately 0.30 and 0.55 with different Marsh cone flow times for each combination. When the w/p-ratio is 0.27 (low), the λ_{25}-value can range between approximately 0.15 and 0.35.It indicates that different w/p-ratios can contain different amounts of A_{25} to achieve sufficient fluidity, i.e. each w/p-ratio is related to a λ_{25}-value interval. The results indicate that higher λ_{25}-values must be combined with higher w/p-ratios and lower λ_{25}-values must be combined with lower w/p-ratios.

Each saturated Marsh cone flow time corresponds to a mini slump flow value. In Figure 13b) the λ_{25}-value is plotted versus the mini slump flow that occurs at the saturation point in the Marsh cone test for different w/p-ratios. It can be seen that lower λ_{25}-value will increase the mini slump flow at the saturation point and the increase seems to mainly depend on the λ_{25}-value.

When the λ_{25}-value is 0.45 the mini slump flow in the saturation point is 320mm for both w/p-ratio 0.33 and w/p-ratio 0.37. The corresponding Marsh cone flow time at this point is approximately 50 seconds and 30 seconds respectively, which means that equal mini slump flow can be achieved with different corresponding Marsh cone flow times depending on how the w/p-ratio is combined with the λ_{25}-value.

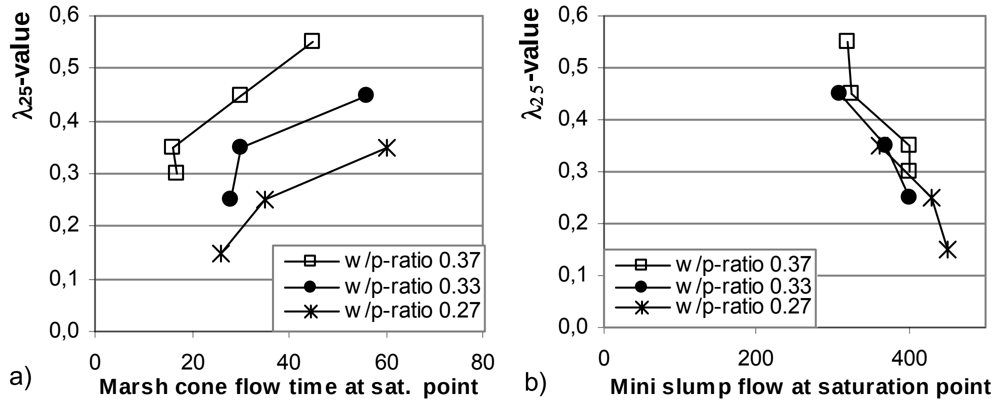

Figure 13 a) The λ_{25}-value plotted versus the Marsh cone flow time at the saturation point for different w/p-ratios. b) The λ_{25}-value plotted versus the mini slump flow when the mix has reached the saturation point in the Marsh cone test.

The described cross effect between w/p-ratio and λ_{25}-value is important when applying micro mortar tests on concrete mix-design. Depending on how the λ_{25}-value is combined with the w/p-ratio; different flow properties can be achieved. The λ_{25}-value/w/p-ratio relation is probably material related.

For this particular case, concrete mixes with higher w/p-ratio can comprise higher A_{25} content, in relation to the total powder content, in comparison with mixes with low w/p-ratio. This effect is probably material related and can be experimentally evaluated.

This phenomenon can be referred to Powers (1932) findings; he concluded that paste with higher water content (higher w/p-ratio) required higher proportions of sand to achieve a certain workability. The results indicate that it is possible to determine, with the suggested experimental test method, an appropriate A_{25} content for a given w/p-ratio.

3.2.4. Concluding remarks

The fluidity of micro mortar is complex; it is influenced of how the constituents are combined and also the properties of the available materials. The λ_{25}-value is an indirect measurement of the fine aggregate to mortar content relation, often used by other authors as a key parameter for fresh SCC. Okamura and Ozawa (1996) suggest that this ratio shall be kept at 40% and Domone (2006b) has shown that a mean fine aggregate to mortar quote is 47% for SCC mixes.

The test results indicate that for a certain fluidity; 1) the λ_{25}-value is a function of type of aggregates used 2) the most appropriate λ_{25}-value is a function of the w/p-ratio and 3) it is possible, with relatively simple test methods, to evaluate an optimal λ_{25}-value for the actual materials. It is thus possible to tailor an appropriate λ_{25}-value regarding w/p-ratio, type of aggregate and desired workability, which might lead to a greater utilization of the constituents.

4 Experimental micro mortar optimization method

4.1 Performance based micro mortar optimization in general

When understanding how different parameters, such as w/p-ratio and the λ_{25}-value, are related to each other and how they affect the fluidity, a structured program for experimental micro mortar optimization can be formulated that generates the most adequate answers to a potential user.

A desired working procedure shall receive information regarding properties that are of importance for further use in concrete. The following properties can be evaluated with the two suggested test methods:

- *Robustness*: A chosen combination of materials shall be robust, i.e. insensitive against outer disturbance. The degree of robustness for different combinations of materials can be evaluated with the two suggested test methods and it has been suggested that the robustness is valued regarding the Marsh cone flow behaviour.
- *Characterization of the flow properties:* Irrespective of method chosen to characterize the fluidity of mortar, a strategy for interpretation must be formulated. This paper suggests that the fluidity shall be classified with a combination of the Marsh cone flow and the mini slump flow. It is thus important to formulate how the results from such tests shall be interpreted and valued regarding the fluidity for further implementation in the concrete.
- *Optimal combination of available materials for the actual application*: With respect to the actual type of application, structural element to be cast, together with demands on strength and durability, the most appropriate combination of materials shall be found that fulfill stated demands on robustness and fluidity. It must thus be possible to formulate whether an interpreted fluidity from the Marsh cone and the mini slump flow is appropriate or not on concrete regarding the application area.
- *The time-factor regarding the chosen superplastisizer*: A consistency/time-diagram can be established for the chosen type of superplastiziser, which makes it possible to decide the target values when mixing in comparison to the demanded consistency at working site.

4.2 Evaluation of robustness

It was discussed in section 3.1.1 that different flow behaviours were identified in the Marsh cone test, denoted Type I, Type II and Type III. To fulfill the demands on high robustness, it has been discussed that a mix preferable shall show a Type II behaviour, which includes a long buffering zone. With the aim to clarify if the Marsh cone flow behaviour is an indication of the robustness, a Type II and a Type III mix have been tested by increasing the water content. In Figure 13, the Marsh cone flow and the mini slump flow is plotted against the increased water content. The initial flow and the superplastiziser dosage used correspond to the flow in the saturation point. It can be seen that the Type II show a lower sensitivity against variations in the water content, in comparison to the Type III mix, since the Marsh cone flow time is nearly unchanged for an 10% water content increase. It is also reflected in the slump flow test. It can be suspected that the behaviour in the Marsh cone test can be an indication of the robustness. It shall be pointed out that a Type I mix unfortunately not has been tested regarding the water sensitivity.

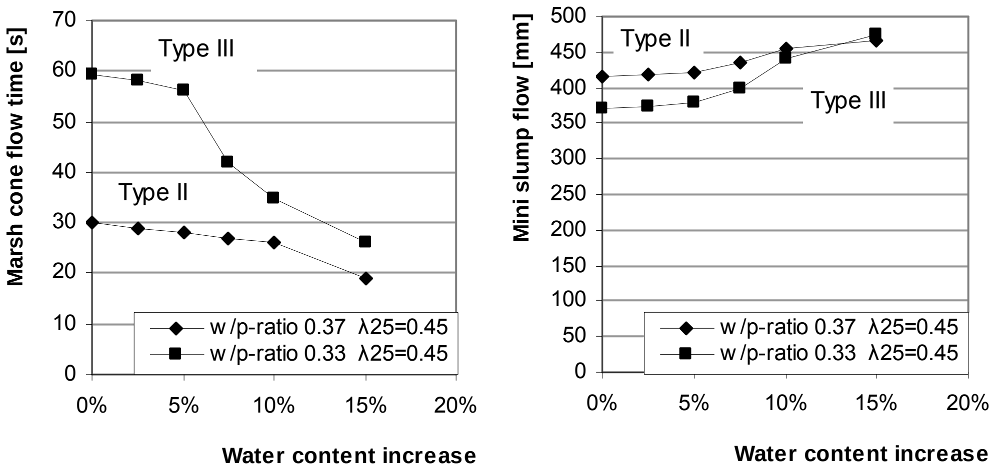

Figure 14 The sensitivity against water content variations for two mixes showing a Type II and Type III behaviour in the Marsh cone test.

4.3 Characterization of the flow properties

The fluidity of paste and micro mortar are often described in terms of rheology, "*the science of the deformation and flow of matter*" (Tattersall et al. 1983). The rheological behaviour of a material can be described by its yield value and its viscosity. The yield stress is defined as the shear stress that must be applied to a material to make it flow. Viscosity is defined as the inclination of the straight line between the shear stress and the rate of shear.

For practical purposes it might not be necessary to characterize a mix regarding yield value and plastic viscosity, an alternative might be a description in function related terms appropriate for the structure element to be cast. The two suggested experimental test methods, mini slump test and Marsh cone test, can together be a rational approach to describe the fluidity of mortar on a functional basis. They shall not be seen as a substitute to describe the flow behaviour in words of rheology, more as an alternative method to characterize and describe the fluidity of paste and mortar.

In earlier sections, the principles for the flow behaviour in the Marsh cone test and the mini slump flow test have been described. For a specific Marsh cone flow time in the saturation point, the corresponding mini slump flow can be either long or short. The Marsh cone flow time can be adjusted by different combinations of the constituents.

For a potential user, the most appropriate combination of the fluidity measured with the two suggested test methods shall be chosen. Different types of applications may benefit from different types of workability, e.g. columns may not benefit from a long flowing SCC. A functional description of the fluidity can thus be: fast or slow, long or short, which can be interpreted with the suggested methods. It receives a functional description of the obtained fluidity for the chosen combination of materials and how it is affected by the type and dosage of the chosen superplastiziser. For practical purposes, it means that four distinct groups of fluidity can be identified.

- Short Marsh cone flow time and long mini slump flow
- Long Marsh cone flow time and long mini slump flow
- Short Marsh cone flow time and short mini slump flow
- Long Marsh cone flow time and short mini slump flow

However, as been pointed out earlier, the mini slump flow can always be increased by an addition of superplastiziser. But, for each addition of superplastiziser the point of segregation will come one step closer. The recommended point to choose is the superplastiziser dosage needed to achieve an appropriate mini slump flow and Marsh cone flow time just after the saturation point has occurred, as illustrated in Figure 15. This point is not close to the point of segregation and it has passed the saturation point, which means that the superplastiziser dosage can both increase and decrease somewhat.

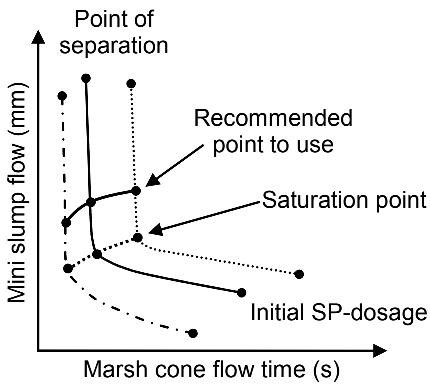

Figure 15 **A schematic illustration of a typical behaviour when combining the Marsh cone test with the mini slump test for three different micro mortar mixes. The recommended point to choose is beyond the saturation point but still relatively far from the point of separation.**

The absolute values regarding both the Marsh cone flow time and the mini slump flow is individual regarding the user's equipment and actual performance of the tests.

4.4 Key parameters influencing the fluidity

When applying micro mortar test results in concrete mix-design, the cross effect between the λ_{25}-value and the w/p-ratio is of great importance because of its direct relation to the total sand content in the concrete mix. The cross effect can be interpreted with the two suggested test methods, and Figure 16 illustrates a w/p-ratio/ λ_{25}-value-diagram that can be established for the actual type of materials. Each w/p-ratio is connected to a λ_{25}-value interval to achieve sufficient fluidity. The upper A_{25} limit corresponds to the highest possible λ_{25}-value that the w/p-ratio can contain to achieve sufficient self-compacting properties and the lowest possible λ_{25}-value for each w/p-ratio will ensure that the mix remain homogenous and does not separate. Changing the λ_{25}-value for a fixed w/p-ratio will also change the flow properties, i.e. numerous of different flow properties can be achieved depending on how the w/p-ratio and the λ_{25}-value are combined. It will thus increase the possibility to choose the most appropriate fluidity for the current application.

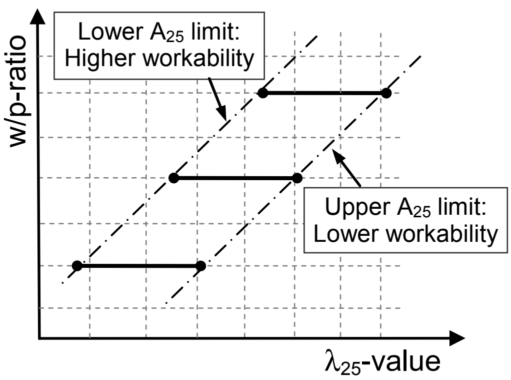

Figure 16 General illustration of the λ_{25}-value intervals connected to a w/p-ratio

Each w/p-ratio corresponds to a specific, material related λ_{25}-value interval, and different d, λ_{25}-values will in the saturation point give different fluidity. It has been concluded that the saturated Marsh cone flow time will increase when the w/p-ratio decreases or when the λ_{25}-value increases for a fixed w/p-ratio. The mini slump flow, measured at the saturation point, will slightly increase for lower λ_{25}-values for a constant w/p-ratio but it will almost retain constant if only the w/p-ratio is changed, as illustrated in Figure 17. However, the mini slump flow can always be further increased beyond the saturation point by adding superplastisizer.

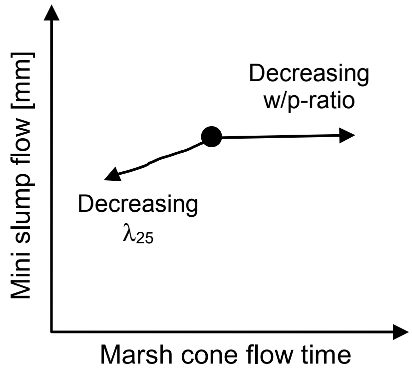

Figure 17 The effect on the Marsh cone flow and the mini slump flow when changing the w/p-ratio or the λ_{25}-value.

By establish a, for the tested materials, w/p-ratio/ λ_{25}-value diagram as suggested, the total sand content and the total amount of binder needed, can be calculated when translated to a concrete mix. In addition, different types of concretes with varying fluidity can be composed depending on how the w/p-ratio and λ_{25}-values are combined. This kind of classification of the fluidity of the micro mortar valid for the available materials will increase the degree of freedom to choose an appropriate concrete mix. It gives a helpful tool for a potential user to make decisions regarding fluidity, demands on w/p-ratio and robustness valued with respect to the structural element to be cast.

4.5 Performance based target values

Interpreting and classifying the fluidity can be performed with different types of methods, e.g. Marsh cone flow time and mini slump flow as suggested in this paper. The next step to fully utilize the potential using micro mortar tests is to characterize the obtained fluidity regarding the field of application. The two flow parameters shall thus be combined regarding the actual type of application, i.e. relate the fluidity to the type of application, which has been suggested for concrete by Wallraaven (2003).

From a rheological point of view, Wallevik (2003) is discussing about the close relation between the two rheological parameters; yield value and plastic viscosity and how these two parameters shall be combined to reach sufficient self-compacting properties. If the viscosity is low, the SCC mix must have a significant yield value to stabilize the mix. On the other hand, if the viscosity is high, the yield value must be low to ensure proper self-compacting properties.

Similar terminology can probably be applied on the proposed experimental test method; Marsh cone test and the mini slump test. A low Marsh cone flow time, i.e. high flow, can preferably be combined with shorter mini slump flow, while high Marsh cone flow times benefit from a longer mini slump flow to ensure that the proper self-compacting properties can be obtained. Each combination will result in different types of concrete with varying properties. For practical concrete mix-design purposes, the chosen combination of materials shall always fulfill the fresh property requirements; filling ability, passing ability and resistance to segregation. As an extra feature, it is more economical if the fresh properties are tailored for the actual type of application.

Figure 18 illustrates a suggestion for how the two suggested test methods can be combined with respect to field of application and expected concrete properties.

The combination of materials and their corresponding fluidity will facilitate the possibility to compose a micro mortar tailored to fulfill the demands in a certain quadrant in the target value diagram.

A slow Marsh cone flow combined with a short mini slump flow might result in a concrete with insufficient self-compacting properties. However, for some applications, e.g. ramps and cambers, such properties might be essential to succeed with the casting. The opposite alternative; fast flow combined with a long mini slump flow can be seen as an unstable concrete with increased risk for segregation. But, if it is a less expensive alternative and the contractor can take that risk, it might be the most appropriate alternative for that specific occasion.

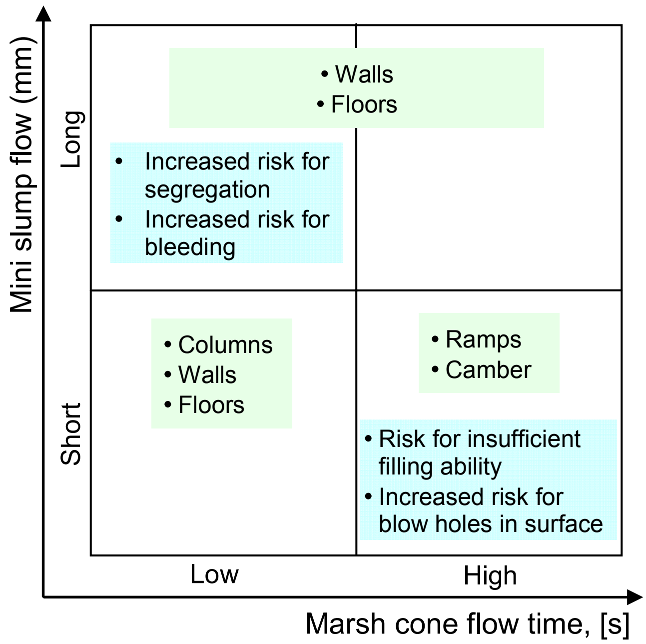

Figure 18 Suggestion to approximate target values for mini slump flow and the corresponding Marsh cone flow depending on type of application.

The suggested experimental optimization method is aimed to be a tool for potential users to make adequate decisions when choosing a combination of their available material for further use in SCC. Concrete production is always a balancing between safe mixes and the price a user is willing to pay. Self-compacting concrete is highly influenced by the properties of the available material and external conditions. If the constituents can be combined with respect to their properties and the field of application, the possibility to compose more tailored concrete mixes might increase.

5 DISCUSSION

Describing the flow properties of concrete, mortar, micro mortar and paste in terms of rheology is well established. It aims to classify a mix regarding its yield value and the corresponding viscosity. However, characterization of fluidity by the science of rheology must be in presence of a viscometer, either for mortar or for concrete. Rheometers are expensive equipment and it might be unnecessary when working with concrete optimization on a practical basis. For concrete producers and concrete optimization aimed to be directly applied in field, the most important concrete properties are robustness and the flow properties. The demands on the fluidity vary depending on the structural application. One type of workability can often be achieved by different combinations of the materials, with a corresponding robustness and price label, i.e. more or less expensive solutions.

A practical mix-design method might facilitate the possibility to judge a concrete mix regarding its fluidity, field of application, economy and also regarding the robustness for different combinations of the local available materials. However, this must not necessarily be expressed in terms of rheology. This paper includes a suggestion to an experimental micro mortar optimization method. It is based in two simple test methods, Marsh cone test and mini slump test, together which will be used to characterize the fluidity of micro mortar.

The proposed test method is intended to be a practical tool when evaluating the influence from available materials on the micro mortar properties. Users can interpret, from very simple test methods, different combinations of constituents regarding flow properties and robustness to form a basis for decisions regarding the optimal combination for a specific type of application. The proposed key parameter, λ_{25}, will facilitate the connection between the micro mortar test and the concrete mix.

There are some very important remarks that shall be pointed out when classifying the fluidity with the suggested test method. First of all, the absolute values; seconds in the Marsh cone test and mm in the mini slump test shall be regarded as unique values only valid for the actual equipment used. The absolute values from the Marsh cone test depend on nozzle opening, filling height and the slope of the cone. The absolute values from the mini slump flow are influenced by the test surface as well as the volume of the cone. It means that absolute test results shall by no circumstances be compared with tests performed with other equipments. It can be seen as a drawback of the suggested method but the main objective with the work has been to develop a simple and practical optimization method mainly aimed to be used for practical concrete optimization, and potential users can characterize actual levels valid for their equipment.

When working with micro mortar and concrete mix-design on a regular basis, it is thus relatively simple to establish reliable levels concerning the levels fast/slow, long/short with the aim to be used as limit values in a classification system. The users can evaluate how combinations of different materials influence the fluidity and the robustness and a unique data-bank can preferable be established as reference values to be used in the future.

The proposed test design method is based on mixes comprising all particles smaller than 0.25mm. Other upper limits of particle size can be chosen, if it is more appropriate regarding the circumstances, but the proposed method with the key parameter, λ_{25}, can still be adopted.

6 CONCLUSIONS

- This paper has shown the potential in finding the most appropriate combination of materials for a specific type of application with two simple tests; the mini slump test and the Marsh cone test measuring the mini slump flow and the flow time through the Marsh cone.
- The proposed test method has proven to be satisfactory to make it possible to answer relevant questions about the micro mortar properties.
- The key parameter, λ_{25}, facilitates the possibility to perform micro mortar tests that are independent from the total micro mortar content in the final concrete mix. The key parameter makes it possible to perform a direct connection between the micro mortar phase and the aggregate phase to create a concrete mix.
- The fluidity of micro mortar is influenced by a cross effect between the λ_{25}-value (the 0-0.25mm to powder ratio) and the w/p-ratio. Generally, higher w/p-ratios must be combined with higher λ_{25}-values to achieve sufficient fluidity. The effect from different combinations of material can be evaluated with the suggested method.
- With the two suggested test methods together with the λ_{25}-value, an optimal fine aggregate content can be found for a specific w/p-ratio and also its corresponding fluidity.

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Paper B

A Method for Practical Aggregate Optimization Aimed for Self-Compacting Concrete Mix-Design

by Sofia Utsi and Jan-Erik Jonasson

A METHOD FOR PRACTICAL AGGREGATE OPTIMIZATION AIMED FOR SELF-COMPACTING CONCRETE MIX-DESIGN

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Abstract

In the present paper three known experimentally based aggregate characterization methods have been tested and evaluated; the degree of packing, the V-funnel flow time and the calculated fineness modulus. The main objective has been to investigate if the properties of aggregates can be characterized regarding their appropriateness for self-compacting concrete. If this is the case, the second aim is to establish a method useful for optimization of aggregate compositions to be used in self-compacting concrete.

The results indicate that one single characterization property seldom is enough to properly describe the influence from an aggregate grading curve on the fresh concrete properties. In addition, it is shown that separate micro mortar tests are essential to get a comprehensive decision-making support on aggregate grading.

A method based on these characterization parameters for choosing an appropriate grading curve due to conditions connected with the structural performance is presented. The proposed optimization method has can give support for decisions regarding choice of aggregate grading curve for different types of structural performance based on demanded consistency and economy.

1 INTRODUCTION

1.1 General

Aggregate is the term for a rock type aimed for concrete production and it is the main constituent in concrete. It can thus easily be understood that the aggregate will significantly affect the properties of the concrete. Aggregate comprises particles with sizes ranging from zero and up to approximately 40mm, depending on application area. It is a natural rounded material or produced by crushing rock, comprising a wide spectrum of properties depending on its mineral composition, particle shape and surface texture. All these properties add to the complexity of making concrete. In addition, it is also a relatively low-cost and strong concrete making material in comparison to other concrete making materials, e.g. cement and mineral additives. Optimizing the use of aggregates in concrete will gain concrete production in a lot of aspects; mainly economical but also hardening, strength and durability properties are affected by the aggregate skeleton.

Among the concrete making materials, aggregates comprise the largest spread in properties and utilizing the available aggregate and its specific concrete making properties can facilitate the increase of the aggregate content in concrete.

1.2 Aggregate composition for concrete

According to Betonghandboken (1997), the most important aggregate properties for concrete mix-design are the gradation curve, filler content, mud content, maximum aggregate size and grain shape. In addition, each particle shape, mineral type and surface texture will affect the concrete properties.
Selecting an aggregate with proper properties and combining aggregates of different sizes to receive an optimal grading curve is the working procedure when choosing aggregates for concrete. The theories about how to receive an optimal aggregate grading curve have been of large interest during the history of concrete development and different suggestions have been reported by many authors, e.g. Fuller and Thompson (1907), Edwards (1918), Abrams (1918) and Powers (1968). Different standardized methods have been proposed with the aim to select an appropriate aggregate grading curve for concrete.

Using a dense aggregate skeleton, termed as the maximum density theory was discussed in the 1920th (Cordon, 1974). It is based on the assumption that a small aggregate void content to be filled with cement paste will improve the concrete strength. Minimizing the paste needed with remaining workability is favorable as it can lower the need for fine material, as it is the most expensive material in concrete. Computer models and practical methods aimed to find the highest degree of packing for a specific type of aggregate has thus become an established method to choose a suitable grading curve. It has been proven to be a satisfactory tool when composing an appropriate aggregate grading curve for concrete reported by Domone and Soutsos (1994), Goltermann et al. (1997), and Haleerattanawattana and Limsuwan (2004).

1.3 Aggregates in self-compacting concrete

Self-compacting concrete (SCC) is supposed to fill the form properly and enclose the reinforcement without any external vibration. The fresh properties of such a concrete are thus essential to succeed with. It means that the demands on the constituents and their composition differ from ordinary vibrated concrete, which is immensely relevant for the aggregate composition. To ensure sufficient fresh concrete properties Skarendahl et al. (2006) have stated the most important property requirements valid for fresh SCC as; filling ability, passing ability and resistance to segregation.

Filling ability: A proper SCC mix shall by its own weight flow and properly fill the formwork and enclose the reinforcement. The properties of the paste or the mortar are most essential to fulfill the requirement of filling ability.

Passing ability: i.e. the resistance against blocking, is an essential performance of SCC as in the end it will affect the filling ability. Blocking is a phenomenon that occurs during concrete flow. Larger particles in the aggregate will have difficulties in passing at narrow sections with dense reinforcement and local variations in concrete quality will be the result (Oh et al. 1997 and Okamura and Ozawa 1996, Okamura, 1997). To avoid blocking the solution has traditionally been to lower the water-to-powder ratio in order to achieve sufficient viscosity, increase the paste content and limiting the coarse aggregate content. To prevent blocking the aggregate composition is thus of great importance.

Resistance to segregation: If there is separation between aggregate and cement in the paste undesired local variations in concrete quality will again be the result. The interplay between aggregate and paste has a dominant role.

As has been pointed out, the coarse aggregate content has traditionally been lowered and replaced by increased paste content to ensure proper fluidity and limitation of the inner particle friction. However, Nielsen et al. (2008) report about successfully used SCC, composed with relatively high aggregate content, approximately 650-700 litres/m^3, which can be compared to 500-600 litres/m^3 from other reports. It can thus be suspected that the aggregate content in SCC can be increased for some types of applications if the grading curve is properly composed.

1.4 Objectives and scope

An aggregate grading curve is a combination of sizes from the available materials. They should be mixed so that the resulting concrete gets the desired properties. These properties should satisfy both the special requirements for SCC and the normal requirements for the structure that is to be erected. One grading curve that is ideal in all cases and for all types of material does probably not exist.

The main objective with this paper is to investigate how aggregate optimization can be performed practically with the aim to improve the properties of self-compacting concrete. The project comprises an investigation of how aggregates of different sizes can be characterized and how a combination of aggregates can be chosen regarding its specific properties and due to stated demands on performance.

The aggregate properties have been characterized regarding its degree of packing, its flow properties together with the calculated fineness modulus. These three parameters are believed to give relevant information on the usefulness of the aggregates. It is investigated if these parameters can be used in practical concrete mix-design. The test methods are chosen based on their simplicity to procure and use.

The paper includes an investigation of the correlation between the chosen test methods and how they can be interpreted with the aim to find the most appropriate aggregate grading curve to fulfill demanded concrete properties.

Questions to be answered are:

- Can aggregate properties, adequate for SCC mix-design, be characterized with the suggested methods?
- How are the suggested test methods related to each other?
- Is the degree of packing an appropriate tool to determine an aggregate grading curve?

- Is the degree of loosely packed aggregates a better tool for choosing aggregate grading curve for SCC in comparison to densely packed aggregates?
- How can an aggregate grading curve be chosen due to the properties of available material, based on the suggested test methods, and due to the performance of the element to be cast?

1.5 Research significance

The main advantages of using self-compacting concrete are improved working environment, increased productivity and the possibility to cast complicated structures. The use of SCC is often accompanied by an extensive quality control program. The material cost for SCC is often significantly higher than for ordinary vibrated concrete. The reason is that the aggregate content is lower in SCC and more expensive cementitious materials and different types of filler are used. An increased use of aggregate would reduce the cost and increase the competitiveness of SCC. It is however essential to fulfil the functional requirements stated for fresh SCC (filling ability, passing ability and resistance to segregation). A systematic aggregate optimization method to compose an appropriate aggregate skeleton regarding its properties and also with respect to the specific type of application might facilitate the possibility to utilize the available materials to a larger extension.

2 LABORATORY TESTS

2.1 Material, test set-up and sample preparation

Two types of crushed material with similar fractions have been investigated in this study, denoted Type I and Type II. The definition of fine and coarse aggregates can vary depending on national standards. In this paper the definition is chosen according to SS-EN 12620, which means that particles passing the 4mm sieve are defined as fine aggregate and all larger particles are defined as coarse aggregate.

Both the tested aggregate types are divided in aggregate fraction 0-4mm, fraction 4-8mm and fraction 11-16mm. From here on, all fractions will be denoted 0-4mm, 4-8mm and 11-16mm. The particle density has been determined by a pycnometer test.
Table 1 shows the tested aggregate compositions where the percentage of each aggregate fraction is by weight of the total quantity tested. Each sample was prepared by combining the dry aggregates from the three different fractions defined in table 1. To receive a homogeneous mix of aggregates, each sample was mixed for two minutes in an ordinary concrete mixer.

Table 1 Tested mixes for both Type I and Type II. Each fraction is in percent of the total sample weight.

No.	0-4mm	4-8mm	11-16mm	Abbreviation
1	100	0	0	100/0/0
2	0	100	0	0/100/0
3	0	0	100	0/0/100
4	80	20	0	80/20/0
5	60	40	0	60/40/0
6	40	60	0	40/60/0
7	20	80	0	20/80/0
8	0	80	20	0/80/20
9	0	60	40	0/60/40
10	0	40	60	0/40/60
11	0	20	80	0/20/80
12	80	0	20	80/0/20
13	60	0	40	60/0/40
14	40	0	60	40/0/60
15	20	0	80	20/0/80
16	60	20	20	60/20/20
17	40	40	20	40/40/20
18	20	60	20	20/60/20
19	40	20	40	40/20/40
20	20	40	40	20/40/40
21	20	20	60	20/20/60

2.2 Dense packing of aggregate

The meaning with dense packing is to find a combination of aggregate that generates the least minimum void content. The total degree of packing is depending on the applied load during the test. Applied packing energy can be calculated according to Eq. 1.

$$P_e = \frac{n}{\frac{V}{m \cdot g \cdot h \cdot N}} \qquad (1)$$

Where P_e= applied packing energy, n= number of falls, V=volume of test container, m=drop weight, g=gravity, h=drop, and N=number of layers.

with the numerical values: P_e= 279kJ/m^3, n=12, V=0.94787dm^3, m=2.5kg, g=9.81m/s^2, h=0.3m, and N=3.

Each combination of aggregate, Nos. 1-21, was tested three times. The prepared sample, as described in section 2.1, was poured into the test container equipped with a detachable border, see Figure 1a. The removable border makes it possible to overfill the test bucket. The bucket was filled in three layers where each layer was compacted with the applied load as calculated in Eq. 1. The border was then removed and the surface was smoothening flat, see Figure 1c, and the bucket including the sample was then weighted, see Figure 1d. The degree of dense packing, ϕ, is calculated as:

$$\phi = \frac{m_{sample}}{\rho_{Agg.particle} \cdot V_{container}} \tag{2}$$

where m_{sample}= The weight of the compacted sample, $\rho_{Agg.particle}$= Particle density, and $V_{container}$= Volume of the test container.

2.3 Loose packing of aggregate

As an alternative to densely packed aggregate, loosely packed material, i.e. aggregate poured into a bucket without any external influence, has been discussed among some researchers as an alternative when applied in self-compacting mix-design. The basic assumption is that loosely packed aggregate is distributed in the same way as in real concrete, i.e. the measured loose packing is supposed to reflect the situation prevailing in a SCC mix and is therefore assumed to be the most appropriate grading.

The prepared samples were poured into the test container without any applied external load. The detachable border was removed and the surface was smoothening flat. The bucket including the sample was then weighted and the procedure was repeated three times for each sample. The degree of loose packing is calculated according to Eq. 1.

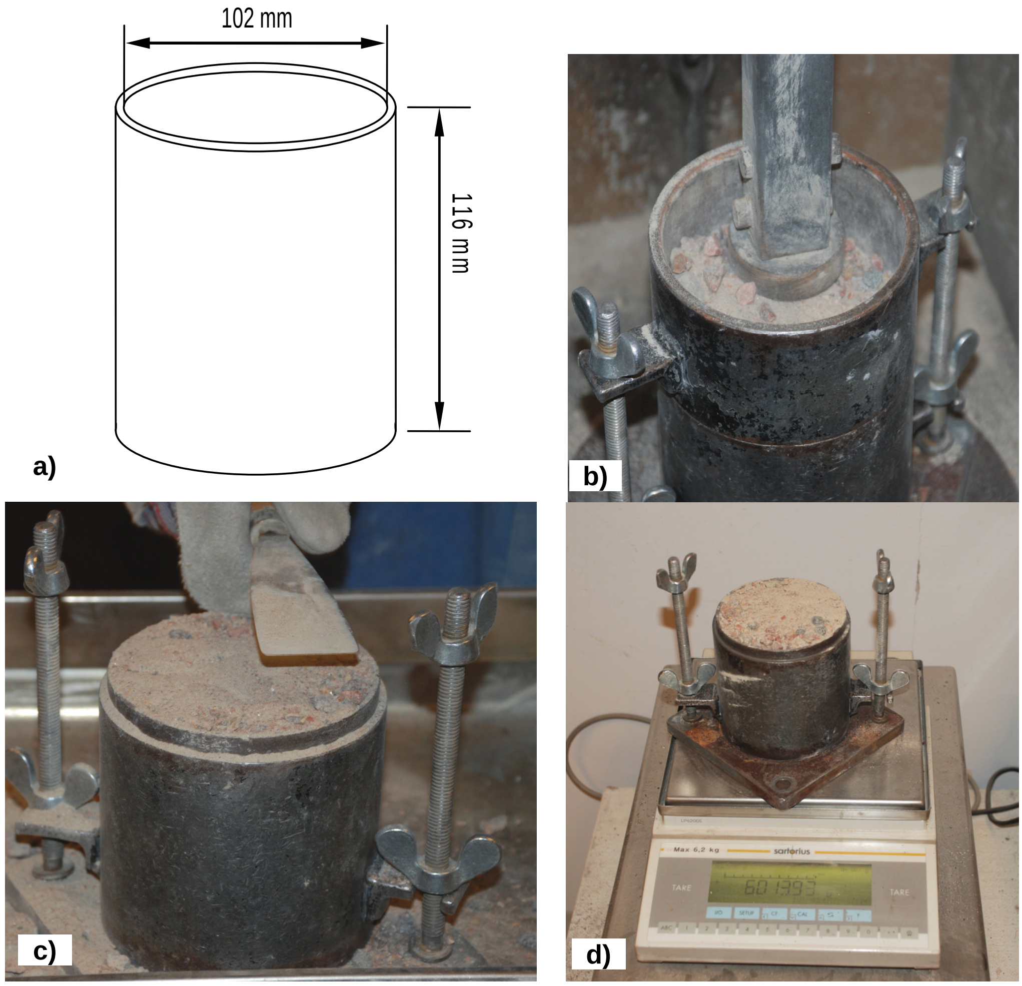

Figure 1 Test procedure for the dense packing test. a) measurements of the test container, b) applied load when packing, c) surface preparation, d) weighing the sample

2.4 Flow measure with V-funnel test

The most essential property for self-compacting concrete is high fluidity. It can be assumed that a high flow of dry aggregate reflects a low friction between the moving aggregate particles. It can thus be suspected that an aggregate skeleton chosen regarding its flow properties in dry conditions can be an alternative to improve the mobility of a SCC mix.

The aggregate flow has been tested with an ordinary V-funnel aimed for SCC, Figure 2, which is chosen due to its simplicity to procure and use. Each prepared aggregate sample was poured into the funnel without any external disturbance. The shutter was opened and the time for the sample to pass out of the funnel was measured. The test procedure was repeated three times.

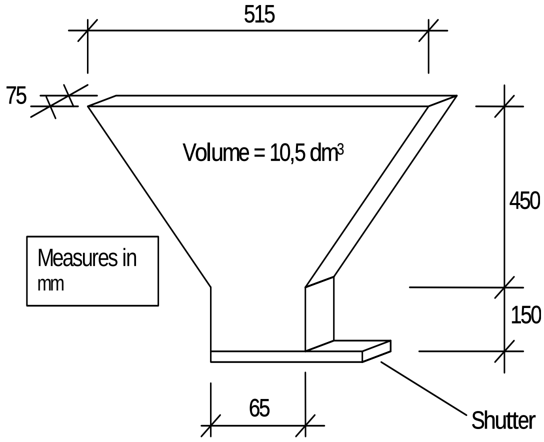

Figure 2 An ordinary V-funnel aimed for testing fresh self-compacting concrete has been used.

2.5 Fineness modulus

The fineness modulus was introduced by Abrams (1918) and can shortly be defined as the area above the grading curve as illustrated in Figure 3. In practice it means that a fine-grained material has a smaller fineness modulus than a coarser material. The fineness modulus is a well established characterization of aggregate when choosing an appropriate aggregate curve.

The fineness modulus is a calculation of the mean particle size for a given grading curve and can be regarded as an indication of the specific surface area of a certain aggregate composition. It does not provide any information about the specific surface area when comparing two different aggregate types; it is only valid for different combinations of aggregate fractions within each aggregate type. Note that the relation between fineness modulus and the specific area shall only be regarded as a description of the coarseness of a combined aggregate. Crushed aggregate for instance, with a raw surface has higher specific area for each particle than smooth natural rounded even if the fineness modulus are equal.

The fineness modulus on its own does not provide sufficient information to base a decision about an appropriate grading curve because two different aggregate types with different surface properties can have almost equal fineness modulus. However, it gives important information in aggregate optimization since lower fineness modulus, compared with a higher value for the same aggregate type, will increase the water demand and the cement paste needed. It is thus desirable to keep the fineness modulus relatively high.

The fineness modulus is calculated by an addition of the remained amount of material on the standard sieves 0.125, 0.250, 0.5, 1, 2, 4, 8, 16. Only half of the remaining material in the 0.125 sieve is included and particles smaller than 0.125mm are excluded. It shall be pointed out that the fineness modulus calculation can vary between different countries. The above mentioned fineness modulus is calculated according to the Swedish method (Betonghandboken 1997).

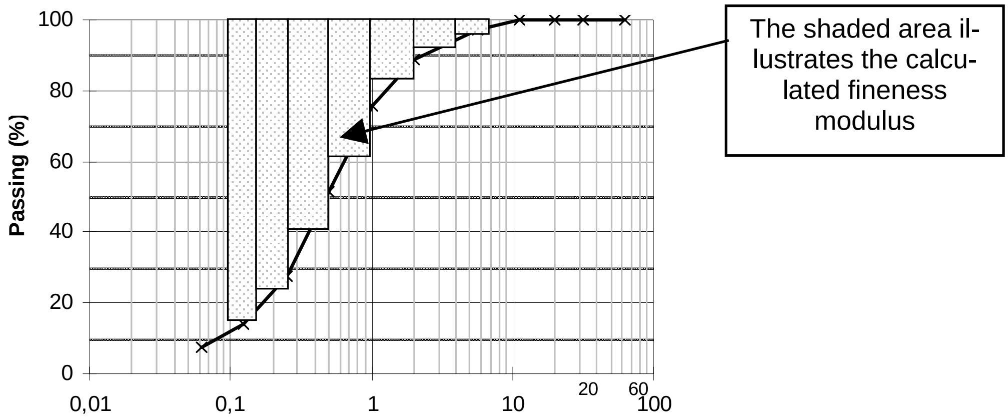

Figure 3 Illustration of a calculated fineness modulus for a grading curve.

3 RESULTS AND ANALYSIS

3.1 Summary of all test results

Each of the three tests was done three times and in table 2 the mean values are given for the dense and loose packing test, the V-funnel test and the calculated fineness modulus. These test results are limited to the 21 tested compositions. However, for concrete mix-design many other proportions not tested here can be used.

As a general summary from the analysis of performed tests, it can be concluded that the fine aggregate content, the 0-4mm fraction, plays a dominant role for the properties of an aggregate composition. The 0-4mm fraction will also influence the relation between the tested characterization methods, e.g. degree of packing, V-funnel flow and calculated fineness modulus.

Table 2 Results from the aggregate tests and the calculated fineness modulus for Type I and Type II.

	Type I				Type II		
No.	Dense packing	Loose packing	V-funnel (s)	Fineness modulus	Dense packing	V-funnel (s)	Fineness modulus
1	0.668	0.536	3.22	2.588	0.672	2.96	3.763
2	0.569	0.499	3.733	5.499	0.598	3.77	5.542
3	0.576	0.486	5.553	6.504	0.590	5.41	6.640
4	0.705	0.587	3.613	3.170	0.697	2.92	4.119
5	0.723	0.617	3.050	3.752	0.682	3.04	4.475
6	0.718	0.635	3.053	4.335	0.673	3.25	4.830
7	0.660	0.613	3.207	4.917	0.625	3.43	5.186
8	0.585	0.506	4.063	5.700	0.614	3.83	5.762
9	0.594	0.531	4.113	5.901	0.624	4.21	5.981
10	0.598	0.527	4.573	6.102	0.624	4.65	6.201
11	0.592	0.502	4.973	6.303	0.618	5.03	6.420
12	0.721	0.602	3.920	3.371	0.708	3.14	4.338
13	0.749	0.639	3.779	4.154	0.719	3.66	4.914
14	0.763	0.642	3.607	4.938	0.721	4.15	5.489
15	0.700	0.584	4.790	5.721	0.677	4.74	6.065
16	0.745	0.628	3.373	3.953	0.709	3.40	4.694
17	0.740	0.647	3.270	4.536	0.697	3.54	5.050
18	0.675	0.637	3.460	5.118	0.650	3.70	5.406
19	0.751	0.633	3.417	4.737	0.710	3.77	5.270
20	0.695	0.619	3.730	5.319	0.675	4.14	5.625
21	0.696	0.652	3.850	5.520	0.681	4.37	5.845

3.2 The degree of dense packed aggregate

Figure 4 illustrates the degree of dense packing in a triangular diagram valid for aggregate Type I and Type II. The shaded area is illustrating the “packing peak”, i.e. the area where the highest degree of packing was reached. For both tested aggregate types, four different aggregate compositions will reach the highest possible degree of packing. Type I reaches a maximum degree of packing in the interval 0.75 to 0.76 and for Type II, the peak appears in the same area with the corresponding degree of packing in the interval 0.71 to 0.72. For concrete mix-design purposes, it means that the least void content for the tested aggregate types can be achieved by relatively many different combinations of aggregate compositions, i.e. the highest degree of packing does not seem to be an absolute value.

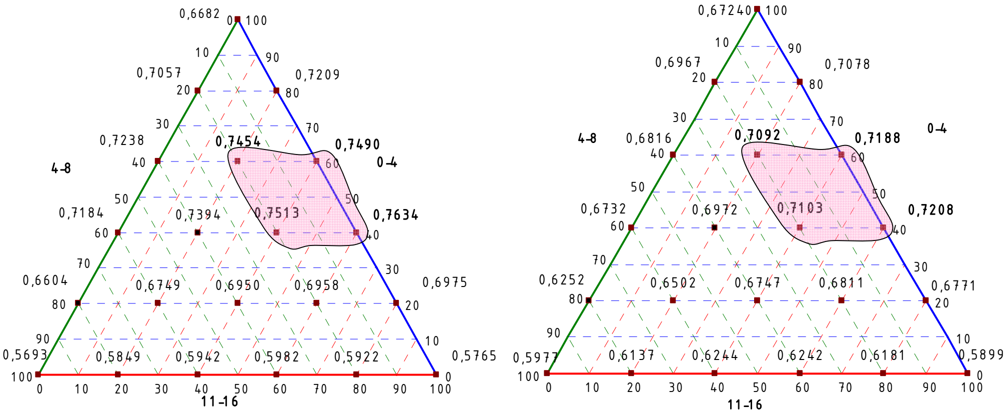

Figure 4 Dense degree of packing illustrated in a triangular diagram. The left figure is valid for aggregate Type I and right figure is valid for aggregate Type II. The shaded area is representing the interval with the highest degree of packing. For Type I this interval is 0.75- 0.76 and for Type II the shaded area is in the interval 0.71-0.72.

When interpreting the results from the packing tests, it can be concluded that the degree of packing is mainly a function of the fine aggregate content, 0-4mm. For the two tested aggregate types, the degree of packing will be almost equal irrespective of the distribution of the 4-8mm and 11-16mm content, which is illustrated in Figure 5 and Figure 6.

In Figure 5 and Figure 6 the degree of packing is plotted versus the 0-4mm content divided in groups of constant 4-8mm content. It can thus be concluded that for a given 0-4mm content, the degree of packing is almost independent from the distribution of the coarse aggregate. This particular behavior has also been reported by Domone et al. (1994). However, there is a slight decrease of the degree of packing for a given fine aggregate content, 0-4mm, if the 11-16mm content is decreased and replaced by 4-8mm, i.e. when the 4-8mm increases. This behavior seems to be valid for both of the tested aggregate types. The maximum degree of packing is obtained when the fine aggregate content, 0-4mm, is in the interval 40% to 60% of the total aggregate content for both tested aggregate types.

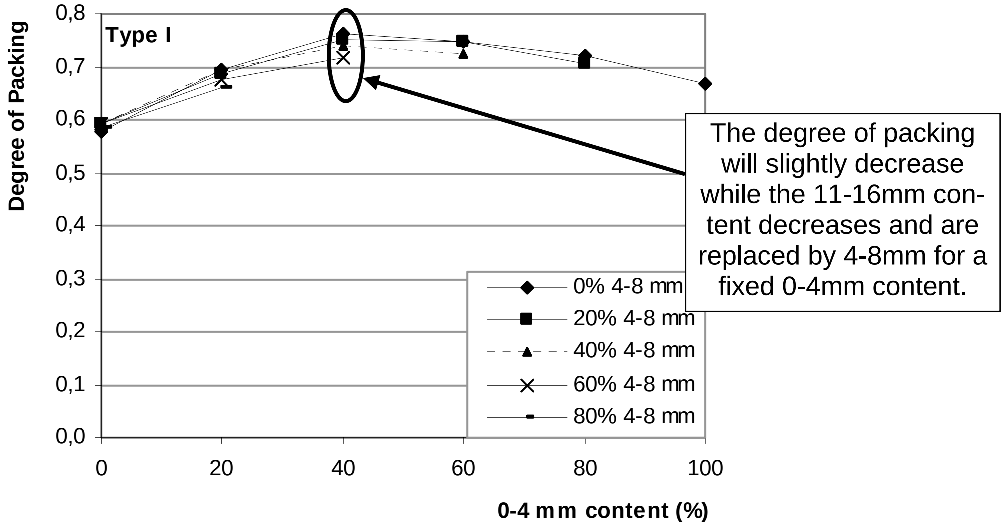

Figure 5 Degree of packing plotted versus 0-4mm content in % of the total aggregate weight for aggregate Type I.

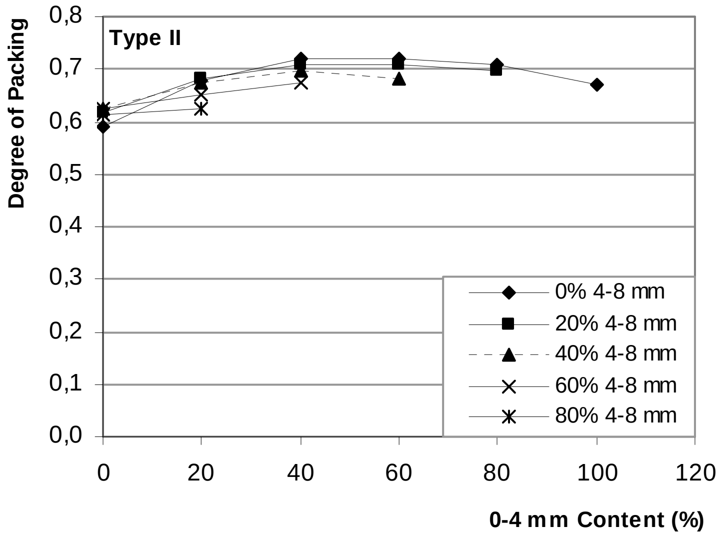

Figure 6 Degree of packing plotted versus 0-4mm content in % of the total aggregate weight for aggregate Type II.

The least void content, when composing aggregate in concrete mix-design, is favorable for two reasons; 1) it will create a stable aggregate skeleton with well graded particles which will act as a ball bearing system when moving, i.e. improved workability, and 2) the void to be filled with cement paste is minimized with remaining workability, i.e. the paste content needed will not be larger than necessary.

However, the interpretation of a packing test is probably more complicated than only searching for the least void content. For instance, a high fine aggregate content will result in high specific surface area, which calls for a higher paste content and also higher water demand. The results from the tests performed in this paper have shown that maximum degree of packing can be achieved with at least four different aggregate compositions with varying fine aggregate content. It can thus be suspected that the degree of packing on its own does not give enough information to base a decision regarding an optimal combination of aggregate in concrete mix-design. Even if the least void content is found, there are other properties that will influence the essential aggregate properties in concrete mix-design, such as the specific surface and the friction between particles.

3.3 The degree of loosely packed aggregate

Figure 7 shows the results from the loose packing test in a tertiary diagram valid for aggregate Type I. It can be seen that the packing peak includes eight, relatively wide spread, aggregate compositions. The basic assumption of using loosely packed aggregate for self-compacting concrete mix-design is that the particle distribution when loosely packed reflects the conditions in a concrete mix. For this particular case, it should mean that eight different aggregate compositions can be classified as appropriate for a SCC mix with respect to maximum degree of packing. These eight aggregate compositions are showing a relatively wide spread in their grading curves and it can be suspected that they will give quite different concrete properties.

It can thus be difficult to interpret such a result when applying them to concrete mix-design. Further, it can also be suspected that the wide spread in peak-values is a result of the uncertainty in the measurement method. A characterization method should be reliable, repeatable and relatively easy to interpret, which seems to be a problem with loosely packed aggregate. It is also not clarified that the distribution of loosely packed aggregate actually reflects the aggregate distribution in concrete. Loosely packed aggregate, just poured into a bucket, might be a relatively uncertain measurement method.

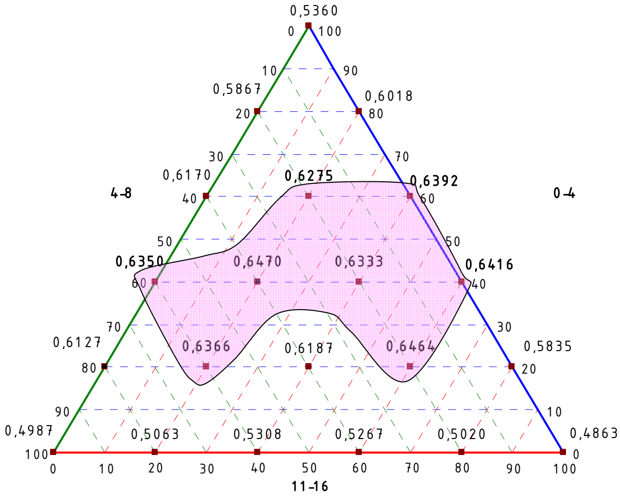

Figure 7 The degree of loosely packed aggregate illustrated in a triangular diagram valid for aggregate Type I. The shaded area illustrates the aggregate compositions that reached the highest degree of packing ranging in the interval 0.63 to 0.65

3.4 The V-funnel flow

3.4.1. Properties affecting the V-funnel flow

The V-funnel flow test used on aggregates is a measurement of the time needed for a certain aggregate composition, loosely piled in the funnel, to flow out. The funnel opening is 65·65mm and the sample flows by gravity. It can be suspected that higher coarseness and higher particle friction will increase the flow time. The particle friction is probably affected by both coarseness and particle shape together with the particle size. For a practical concrete mix-design procedure it is desirable to have a simple and reliable test method to estimate a collective effect of these properties.

According to Kennedy (1940), an excess of cement paste between the aggregate particles is very important to ensure workability of concrete. Friction between the aggregate particles will decrease workability of the concrete if the paste content is not high enough. Further, Okamura (1997) is describing that blocking is related to the direct contact between aggregate particles when passing a narrow space. The traditional solution to prevent blocking has been to lower the water-to-powder ratio or increasing the paste content, which will result in a limitation of the coarse aggregate content. However, if the particle friction is limited in the dry aggregate skeleton, the paste needed to manage the friction and blocking criteria might be decreased. Based on these assumptions, it would be preferable to use an aggregate composition with a fast V-funnel speed for self-compacting concrete.

The interpretation of the results from the V-funnel tests show that the flow time will decrease significantly when the 0-4mm content increases, see Figure 8. Furthermore, for each group comprising a fixed 0-4mm content, the V-funnel flow time will also decrease if the 11-16mm aggregate content is decreased and replaced by 4-8mm, i.e. when the fineness modulus is lowered.

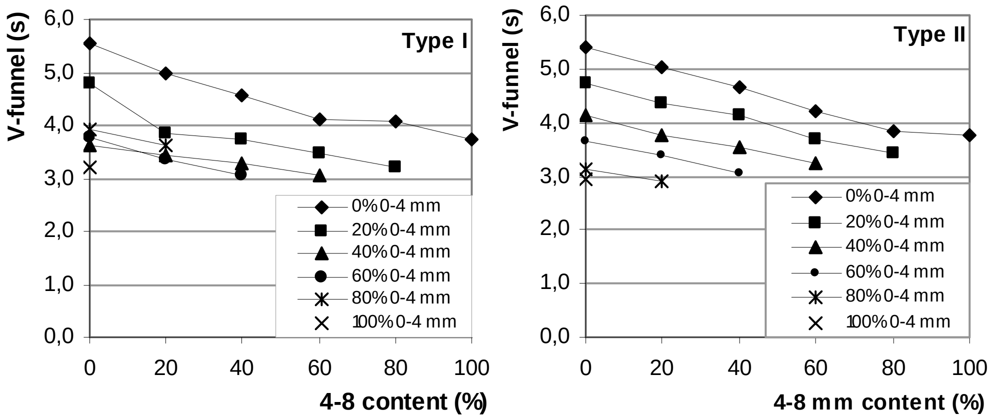

Figure 8 V-funnel flow time plotted against the 4-8mm content for a fixed fine aggregate content, 0-4mm, valid for a) aggregate Type I and b) aggregate Type II.

3.4.2. V-funnel flow in relation to the degree of packing

A grading curve based on densely packed aggregate is assumed to result in a stable aggregate skeleton with a ball-bearing effect when moving. It is favourable because sufficient workability can be obtained with a lower paste content Based on this assumption it can thus be suspected that a high degree of packing will improve the V-funnel flow.

In Figure 9 the degree of packing is plotted versus the V-funnel flow time for aggregate Type I and Type II, respectively. They are grouped by their fine aggregate content, 20%, 40%, 60% and 80-100% 0-4mm. It can be concluded that there is a general relation between the degree of packing and the V-funnel flow time, where increased packing will result in lower V-funnel flow time, which is illustrated by the arrows in Figure 9 a and b.

When interpreting the results with respect to their fine aggregate content, 0-4mm, the results show a slightly different behaviour. For a given 0-4mm content, 20%, 40%, 60% and 80-100%, the V-funnel flow time will slightly increase as the degree of packing increases. Assume that the fine aggregate content is 40% of the total aggregate content. For this case, the lowest V-funnel flow time can be obtained when the 4-8mm content is 60% and the 11-16mm content is zero. If the 4-8mm content is decreased and replaced by 11-16mm, the degree of packing will increase but at the same time, the V-funnel flow time will slightly increase. In this particular case, also the fineness modulus will increase. This phenomenon is valid for all different contents of 0-4mm and is also valid for both tested aggregate types.

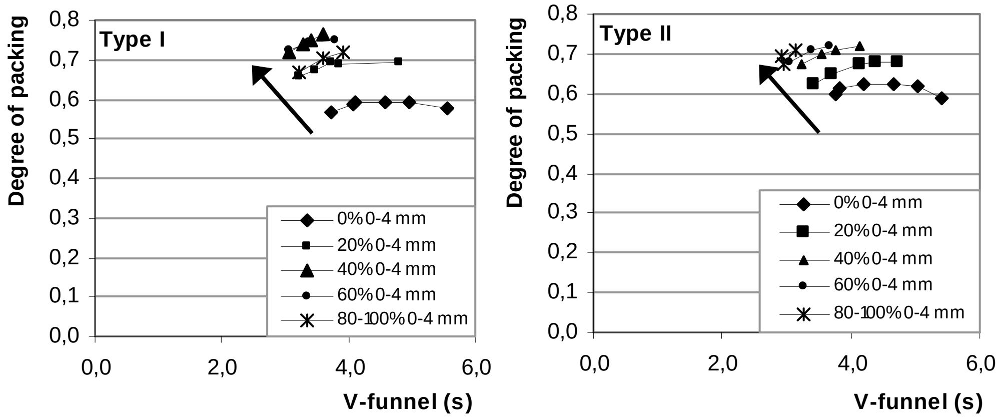

Figure 9 Degree of packing plotted versus the V-funnel flow for aggregate Type I and aggregate Type II. The arrow in each figure represents the obtained general trend; the V-funnel flow will decrease while the degree of packing increases.

3.5 The fineness modulus

3.5.1. Fineness modulus in relation to the degree of packing

Fineness modulus indicates the specific surface of the aggregate. The specific surface influences the needed amount of paste to make the concrete workable. High degree of packing reduces the paste needed to fill the remaining void. It can thus be an alternative to add the fineness modulus as a parameter when interpreting a packing result.

It has been concluded that the degree of packing, for the aggregates tested here, mainly is a function of the fine aggregate content, which is also reflected in the relation between the degree of packing and the fineness modulus, illustrated in Figure 10 and Figure 11. In these two figures the degree of packing is plotted against the fineness modulus grouped by the 0-4mm content. A general trend is that the degree of packing will slightly increase as the fineness modulus increases until a peak value of the packing is reached. Beyond the peak value, the degree of packing will dramatically decrease when the fineness modulus continues to increase.

If Figure 10 and Figure 11 are interpreted with respect to a fixed fine aggregate content, 0-4mm, it can be seen that the degree of packing will increase as fineness modulus also increases. This reflects the results discussed in section 4.1 regarding the V-funnel flow time. For a given 0-4mm content, the degree of packing increases as the 4-8mm content decreases and is replaced by 11-16mm.

As illustrated in Figure 10, an almost equal degree of packing, 0.72 to 0.76, can be reached with a relatively wide spread in the fineness modulus, 3.8 to 5.0, which is mainly a result of the fine aggregate content. It can also be seen in Figure 10 that an equal fineness modulus, e.g. 5.8, can result in aggregate compositions with a degree of packing that is either 0.57 or 0.70.

It is desirable to choose the fineness modulus as high as possible because of the strong correlation between fineness modulus and water and paste demand. However, the void to be filled with paste will decrease at increased packing. Cement paste needed is thus a combined effect of both the free voids to fill with paste and the aggregate surface to be covered with paste. The optimal combination is theoretically small voids together with a small aggregate surface area.

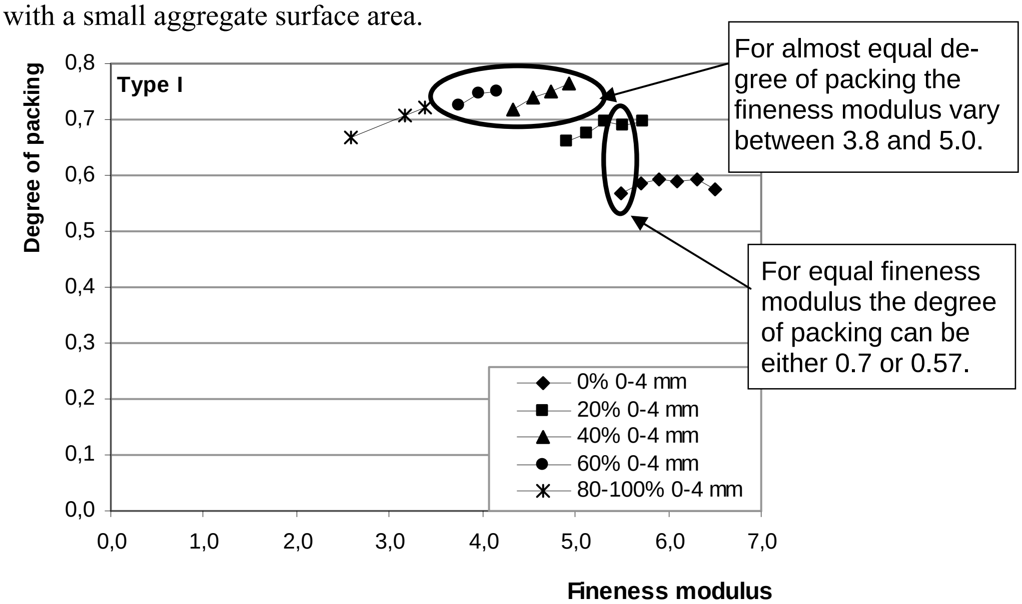

Figure 10 Degree of packing plotted against the fineness modulus grouped by the fine aggregate content, valid for aggregate Type I.

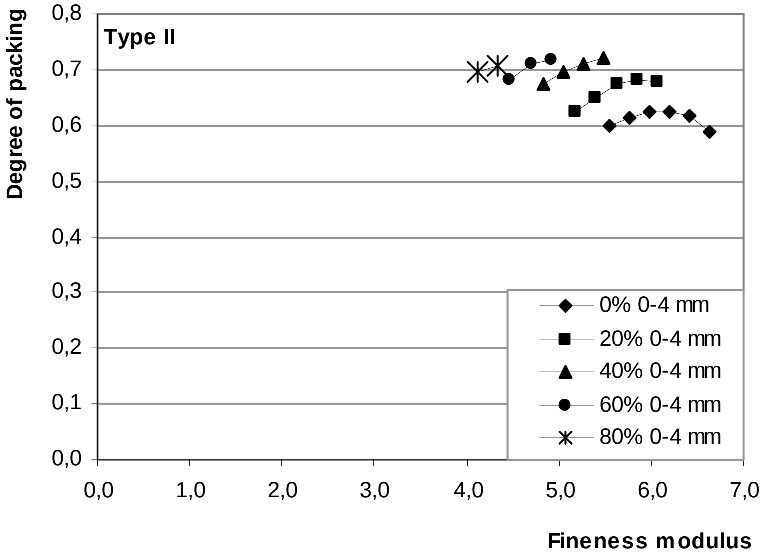

Figure 11 Degree of packing plotted against the fineness modulus in groups of a fixed fine aggregate content, valid for aggregate Type II.

3.6 Concluding remarks from the laboratory tests

The evaluated practical aggregate tests have shown some main tendencies that can be summarized as;

- The degree of packing is mainly a function of the fine aggregate content and high packing degree can be reached with different aggregate compositions. For a given fine aggregate content, there is a small decrease in the degree of packing while the coarser aggregate proportions are changed, i.e. the 11-16mm is decreased and replaced the 4-8mm. For any given fine aggregate content, the highest degree of packing will be reached by a gap graded aggregate, which in this paper means 0% 4-8mm.

- The V-funnel flow is mainly a function of the fine aggregate content where higher fine aggregate contents significantly improves the V-funnel flow, which also decreases the fineness modulus.

- The V-funnel flow is also a function of the proportions of the coarse aggregate. For a given fine aggregate content, every increase of the 4-8mm content will improve the V-funnel flow and an increase of the 11-16mm will decrease the V-funnel flow.

- High packing degree is partly related to a fast V-funnel flow.

Test methods aimed at optimizing an aggregate composition for concrete shall make it possible to interpret the effect of a wide set of aggregate properties, e.g. particle size, surface texture, particle shape. These aggregate properties will altogether influence the concrete mix and its corresponding properties. The evaluated test methods together with the fineness modulus have shown some significant relations. In Figure 12, the V-funnel flow is plotted versus the degree of packing for aggregate Type I and Type II, which forms an elliptic area. In addition, packing and the calculated fineness modulus are also related for both of the aggregate types in a similar way.

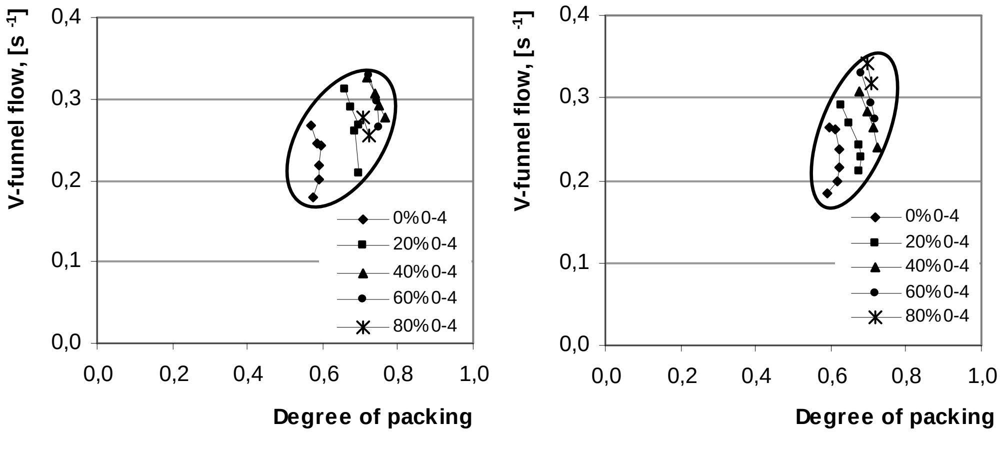

Figure 12 Relation between V-funnel flow and degree of packing for the two tested aggregate types, left figure valid for aggregate type I and right figure for aggregate type II.

The relation between V-funnel flow, degree of packing and the fineness modulus can thus generally be illustrated with an elliptic area as illustrated in Figure 13. It is a general trend that higher degree of packing will improve the V-funnel flow, which has been shown to be an effect of increased fine aggregate content, illustrated with the red dashed line in Figure 13. If the 0-4mm content decreases, the fineness modulus will increase and the V-funnel flow and the degree of packing will decrease. For a given 0-4mm content along the red line, the degree of packing can be improved by a redistribution of the coarse aggregate, illustrated with the blue dashed line. By decreasing the 4-8mm content and replace it with 11-16mm, the degree of packing will increase, which also means that the fineness modulus will increase. Analogous, the flow can be improved for a given 0-4mm content along the red line. By decreasing the 11-16mm and replacing it with 4-8mm, the V-funnel flow will be improved and the fineness modulus will be decreased. Increased V-funnel flow will always result in a decreased fineness modulus.

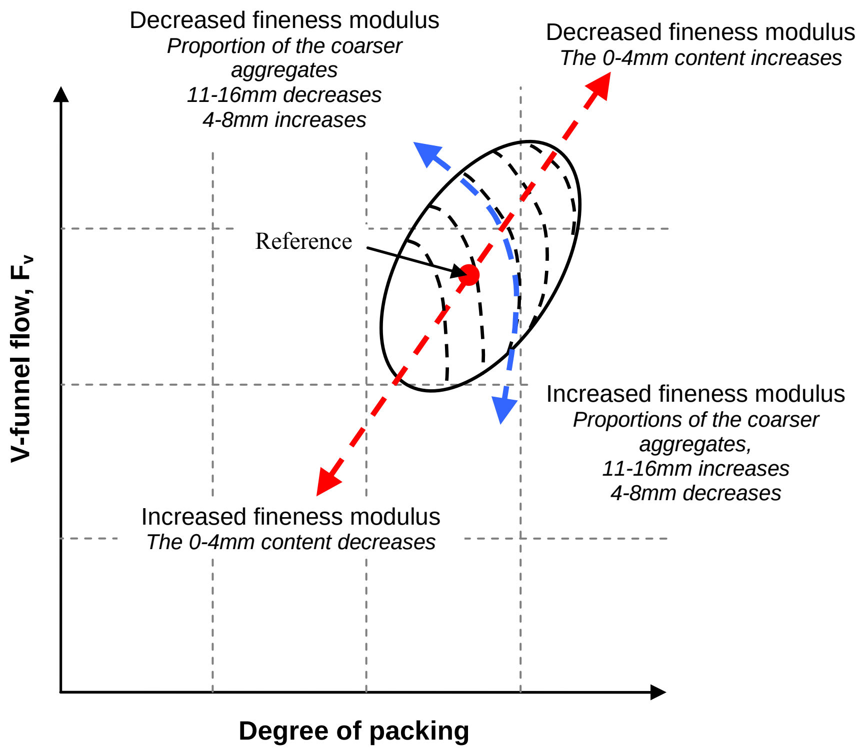

Figure 13 Illustration of the relations between packing degree, V-funnel flow and fineness modulus for dry aggregate.

The elliptic area illustrated above can preferably be established for a chosen type of material since it gives a quick overview of the interaction between the parameters; degree of packing, V-funnel flow and fineness modulus.

4 METHOD FOR AGGREGATE OPTIMIZATION AIMED FOR SCC

4.1 Demanded concrete properties to fulfil

The main objective when choosing an aggregate grading curve aimed for SCC is to fulfil, besides demands on strength and durability, the fresh properties requirements; filling ability, passing ability and resistance to segregation, see chapter 1.3

One of the basic ideas when optimizing the aggregate skeleton for SCC is to utilize the properties from the available material and to tailor the mix regarding structural performance, which might improve the cost-effectiveness. Decisions shall thus preferably be based on material related behaviour in combination with demanded workability and the properties of the element to be cast.

4.2 Conditions for choosing an appropriate grading curve

Concrete can be regarded in its fresh phase as solid particles, cement, aggregate and mineral additives, suspended in water. Choosing an appropriate aggregate grading curve shall thus include the influence from all solid particles in concrete since they will all together affect the properties of the fresh concrete. However, the influence from cement and mineral additives in concrete can be taken into consideration by regarding aggregate suspended in paste, cement, water and mineral additives.

Powers (1932) was discussing how different sand content influences the workability of fresh concrete when combined with varying water-to-powder ratios. Powers stated that for a given water-to-cement ratio and demanded workability, there is an optimal sand content. By optimal, Powers meant the least cement content needed. Further, Powers stated that if a given water-to-cement ratio was combined with its corresponding optimal sand content, the distribution of the coarser fractions will be of secondary importance regarding cement requirement and workability. Powers meant that the maximum density of aggregate is not the most important parameter for choosing the sand content, but the optimum sand content will probably be close to the densest aggregate composition.

The effect of the fine aggregate content in combination with a given paste is a commonly used parameter in self-compacting concrete mix-design, called the fine aggregate to mortar quote. This quote is one of the key parameters determining the workability of the mortar, which also influences the concrete workability. Okamura (1997) is suggesting that the quote shall be approximately 40%. Domone (2006) presented an evaluation of successful applications of SCC where the average fine aggregate to mortar quote for the evaluated mixes was 47%.

In paper A in Utsi (2008), an experimentally based method for choosing the most appropriate content of fine aggregate in micro mortar aimed for SCC is suggested. The content is chosen with respect to the properties of available material, the water-to-powder ratio and the level of demanded workability. With the suggested method, the so called λ_{25}-value can be evaluated. λ_{25} is defined as the most appropriate ratio, for the demanded workability, between the finest aggregate particles and the total content of cement and mineral additives. Since it is experimentally based, it is a material related parameter that is a direct connection between the micro mortar phase and the aggregate grading curve.

When an aggregate grading curve is to be selected, it can be based on results from the three suggested characterization methods; degree of packing, V-funnel flow and fineness modulus. However, it has been concluded that similar degree of packing can be achieved from aggregate compositions with different fine aggregate contents. The suggestion to an interpretation of an aggregate test with the aim to choose an appropriate aggregate grading curve is based on:

- the fine aggregate content
- the demands on passing ability
- the properties of the paste to be used

4.3 Method for selection of an aggregate grading curve

4.3.1. The fine aggregate content

From the results presented in this paper it has been concluded that the degree of packing is mainly a function of the fine aggregate content. High packing can be received with an interval of fine aggregate content. The size of this interval will probably vary depending on the aggregate type. The fine aggregate content in concrete will, in addition, highly influence the fresh concrete properties.

The first step in the suggested aggregate optimization method is thus to identify the Fine Aggregate high packing INterval, denoted hereafter as the FAIN-interval, see Figure 14. It is the interval of fine aggregate content where the highest degree of packing occurs.

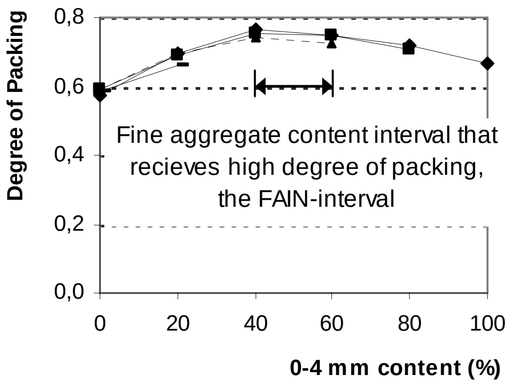

Figure 14 Identifying the fine aggregate content interval where the highest degree of packing occurs, i.e. the FAIN-interval.

4.3.2. The demands on passing ability

The demands on passing ability are mainly based on the structural element to be cast and can thus vary between low or high demands. To manage high passing demands, it can performed by replace the coarse aggregate content with fine aggregate content or it can be performed by composing the coarse aggregates in a manner that facilitate the passing through narrow spaces. Depending on how the fine aggregate content is chosen within the FAIN-interval, the remaining coarse aggregate content will vary.

Low demands on passing ability: The fine aggregate content can be low within the FAIN-interval. If the concrete can manage the blocking criteria when paste is added, it might be an economical solution.

High demands on passing ability: The distance between the coarse aggregate particles can be increased by either a high fine aggregate content or a lower fine aggregate content together with increased paste content, or these two alternatives together. The interaction between the fine aggregate content and the paste content is discussed in the next section.

The coarse aggregate gradation can also be based on the V-funnel flow test results. Higher V-funnel flow is an indication of the inner particle friction between the aggregate particles. It has been concluded, based on the results presented in this paper, that higher V-funnel flow can be achieved when the coarsest particles are decreased.

4.3.3. The properties of the paste

Filling ability shall always be fulfilled in a SCC mix. It can however be achieved with different degree of workability, which is mainly a function of the workability of the mortar, i.e. the relation between cement paste and fine aggregate content.

The relation between the paste properties and the fine aggregate content can be evaluated experimentally with the method suggested in paper A in Utsi (2008). However, generally it can be said that higher fine aggregate content demands higher paste and water content in comparison to lower fine aggregate contents (Powers, 1932). Choosing an appropriate aggregate grading curve shall thus also include the properties of the cement paste aimed to be used.

In case of low water-to-powder ratio, the fine aggregate content can be chosen from the lower limit in the FAIN-interval, since lower w/p-ratio generally shall be combined with lower fine aggregate contents. However, it might happen that blocking or particle interference occurs. The fine aggregate content and the corresponding paste content must than be further increased to increase the distance between the coarse aggregate particles.

In case of relatively high water-to-powder ratio, the fine aggregate content can be chosen from the upper limit in the FAIN-interval, even if combined with moderate paste content, since higher water-to-powder ratio normally can comprise higher fine aggregate contents. It will automatically result in lower coarse aggregate content.

4.3.4. Working procedure for the aggregate optimization

To fully utilize the potential with an aggregate optimization, decisions shall be based on the common effect from some important factors. The working procedure for how an aggregate grading curve can be chosen based on material related parameters is illustrated in Figure 15.

From the packing test, the interval of fine aggregate content that receives the highest degree of packing can be determined, i.e. the FAIN-interval is established. The chosen fine aggregate content shall be based on the FAIN-interval, the properties of the paste to be used and the demands on passing ability.

The coarse aggregate gradation is determined from the V-funnel flow test together with the calculated fineness modulus. Higher V-funnel flow can preferable be used in case of high demands on passing ability. A higher fineness modulus can be the decisive factor in case of low demands on passing ability.

From the chosen fine aggregate content, the coarse aggregate content can be calculated. An initial trial mix can be composed, based on all materials to be used and demands on the cement paste.

The trial mix can be evaluated based on established test methods for self-compacting concrete. Adjustments shall be performed based on the observations from the trial mix.

A full description of how a SCC mix can be composed, based on aggregate optimization and micro mortar tests, is presented Utsi (2008).

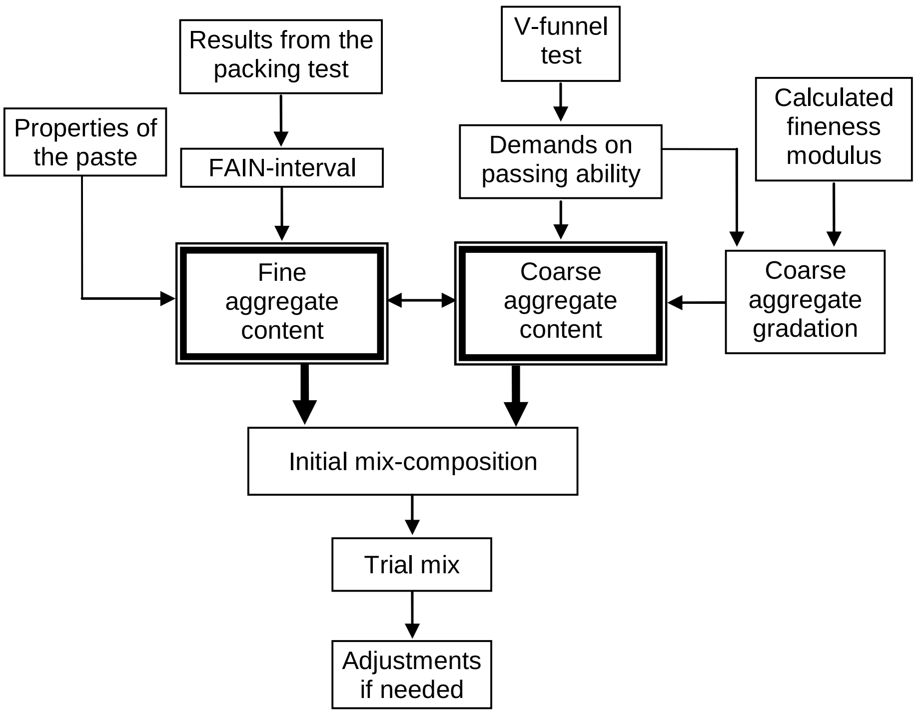

Figure 15 Suggested working procedure for an aggregate optimization based on the suggested test methods.

5 DISCUSSION

The aggregate optimization method proposed in this paper is based on three known test and evaluation methods; degree of packing, V-funnel flow and fineness modulus. These three key parameters will together sufficiently describe the complexity of aggregate properties that are of importance for concrete mix-design, here with focus on properties valid for self-compacting concrete. The results from this paper is showing the potential in putting more efforts in the aggregate optimization and the possibility to connect a specific grading curve to stated performance specifications.

It has been discussed, based on performed tests, that one single aggregate characterization method seldom is enough for a proper interpretation with respect to the influence from an aggregate grading curve on the fresh concrete properties. It has been concluded that the highest packing for both of the tested aggregate types will be obtained when the fine aggregate content is ranging from 40% to 60% of the total aggregate content. In a concrete mix, these two amounts will affect the concrete properties differently because of the close relation between fine aggregate content, paste content, water content and mortar workability. A high packing degree is often declared to decrease the paste content needed for remained workability, since the voids to be filled with paste will decrease, Goltermann et al. (1997). However, the paste shall, in addition to fill the free voids, also enclose each aggregate particle. The aggregate surface area will thus highly influence the paste content needed. The fineness modulus is an indication of the surface area of an aggregate grading curve and the results have shown that equal high packing can be obtained for aggregate compositions with a relatively wide spread in fineness modulus. Choosing an aggregate grading curve only based on the highest degree of packing can be misleading since the particle surface area also highly influences the paste content needed. It is thus essential, when working with aggregate optimization, to know how to interpret the results properly to receive the most appropriate grading curve for a specific application.

The relation between fine aggregate, water content and content of cement and mineral additives is essential regarding the workability of self-compacting concrete. Thus, an aggregate optimization by its own does not provide sufficient information to make adequate decisions regarding the combinations of aggregate since concrete is a matrix of all solid particles, including cement and mineral additives, suspended in water. The suggested method is based on Powers theory about “the optimal sand content”, and it is here suggested that also the composition and properties of the paste are included. It will facilitate the possibility to choose aggregate grading curve based on the properties of all included solid particles in concrete and its relation to water demand.

The potential in establishing a description of the aggregate characteristics, together with the knowledge of the corresponding paste, offers a support for decisions regarding the optimal aggregate grading curve for a specific demand on consistency and economy of the concrete mix.

6 CONCLUSIONS

Based on obtained test results and evaluation of the interaction between them, the following conclusions are made:

- It has been concluded that results from three test methods; degree of packing, V-funnel flow time and fineness modulus, mainly are depending on the fine aggregate content.
- It has been concluded that the three tested key parameters are strongly related to each other and the interaction can be illustrated by an elliptic area describing V-funnel flow as a function of the degree of packing for different aggregate compositions.
- The results from this paper indicate that one single aggregate characterization method seldom is enough for decisions regarding the most appropriate aggregate grading curve.
- Choosing an aggregate grading curve can be based on the fresh SCC properties requirements; filling and passing ability, chosen in accordance with the structural performance conditions.
- Loosely packed aggregate have been tested and evaluated as a parameter in SCC mix-design. It was concluded that loosely packed aggregate, just poured into a bucket, might be a relatively uncertain method with a high number of compositions with almost the same high degree of packing. It can be difficult to interpret such a result when applied on concrete mix-design.
- An aggregate characterization method shall be reliable, repeatable and relatively easy to interpret for further use in concrete. The full potential with an aggregate optimization can be achieved when the material related parameter describing the interaction between fine aggregate and paste properties is included.

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Paper C

Heat and Strength Development for Concrete Containing Fly Ash

by Sofia Utsi and Jan-Erik Jonasson

HEAT AND STRENGTH DEVELOPMENT FOR CONCRETE CONTAINING FLY ASH

Sofia Utsi and Jan-Erik Jonasson, Luleå University of Technology

Abstract

This paper presents a numerical tendency model for evaluation of heat and strength development for concrete containing fly ash in different amounts. With the presented model, parameters for heat and strength development calculations in early age can be calculated. It facilitates the possibility to evaluate e.g. form removal times and estimations of need for protection against early freezing for concrete mixes containing fly ash in different amounts.

1 INTRODUCTION

1.1 Heat development and strength growth

Hydration in concrete is an exothermic chemical reaction. A few hours after the concrete have been mixed, the reaction between water and cement starts to generate heat and the strength growth begins. The strength development is strongly related to the heat development, which is influenced by the chemistry of the binder and by the curing temperature. The temperature effect on the rate of hardening can be expressed by the temperature factor, which also is known as the "maturity function".

For the hardening control of young concrete, the knowledge of the maturity and the temperature development is essential to be able to plan and control the production properly. It involves estimations of form removal times, assessments of necessary times for moisture curing of the concrete surface, and estimation of conditions to avoid too early freezing of the young concrete.

1.2 The effect of fly ash on young properties

Fly ash is a pozzolanic material, which means that it reacts with the calcium hydroxide $Ca(OH)_2$ that is produced when cement reacts with water. When fly ash reacts with $Ca(OH)_2$, calcium silicate hydrate (CSH) is formed, which means that the content of the durable material (CSH) increases in the concrete (Papadakis et al., 1992 and Fraay et al., 1989).

The in-corporation of fly ash in concrete can be performed in three different ways, Berry and Malhotra (1980):

1. Exchange cement with fly ash by weight on a 1:1 basis
2. Exchange parts of the cement and parts of the aggregate
3. Adding fly ash in addition to the cement as a part of the fine aggregate

According to Cannon (1968) fly ash contributes to the concrete strength in three different ways; by a water reduction because demanded workability can be received at lower water contents when fly ash is added, by an increased effective paste volume and by the pozzolanic reaction. The first two will influence the early concrete strength while the latter will contribute to increased long-term strength.

Any replacement of Portland cement with fly ash in concrete will influence the compressive strength, and the strength growth may be low in the beginning, but the growth usually continues up to at least 6 months (Berry and Malhotra, 1980). It is well known that in order to maintain the 28-days compressive strength the amount of fly ash added always exceeds the amount of cement removed (Cannon, 1968). This points out that the relation between fly ash and cement is one of the decisive parameters describing the strength growth.

Fly ash in concrete is not common in Swedish concrete production, mainly because of the lack of national produced fly ash. However, there is an increased interest among concrete producers to use fly ash in concrete, mainly as a replacement of a part of the cement content. A tendency model is needed to assess the effects of using fly ash in different applications. The strength, as well as generated heat, is dependent on the fly ash content in relation to the cement content, and a model to predict strength and heat have to consider the actual binder composition in a consistent way.

1.3 Objectives and Scope

The main objective with the work presented in this paper is to establish a numerical tendency model for heat development and strength growth in concrete containing fly ash in different amounts. Further, data from a tendency model shall be possible to use in structural analyses to be able assess effects of using variable fly ash contents for different structures at different conditions as a part of a production planning.

The heat development is tested with semi-adiabatic tests and the strength development is measured by compression tests of cubes cured in water at different temperature levels. Tests have been performed on concrete with two different water-to-cement ratios containing fly ash in three different amounts.

The tested mixes are composed with one type of fly ash, one type of aggregate, one type and dosage of superplastiziser as well as one type of cement with the aim to evaluate the pure effect from the fly ash content in combination with two levels of equivalent water-to-cement ratios. The tendency model is expected to reflect the combination of variable fly ash and variable water content.

2 LABORATORY TESTS

2.1 Material properties and Test program

Concretes containing different amounts of fly ash can be characterized by the equivalent water-to-cement ratio, w_0/C_{equ}, calculated according to Eq. 1. In recommendations and codes the efficiency factor in Eq. 1 is given specific values.

$$\frac{w_0}{C_{\mathrm{equ}}} = \frac{w_0}{(C + k \cdot FA)} \qquad (1)$$

where w_0= mixing water content [kg/m^3], C_{equ}= equivalent cement content [kg/m^3], C = cement content [kg/m^3], FA = fly ash content [kg/m^3], and k = efficiency factor [-]. Also the allowed maximum content of fly ash is regulated in recommendations and codes with different values depending on the application situation.

The tests have been performed due to the test program presented in Table 1, where two different equivalent water-to-cement ratios with four different fly ash contents have been included. This generates 18 different mixes. For each value of w_0/C_{equ}, either 0.4 or 0.5, the water content and the equivalent cement content have retained constant. The use of an efficiency factor less than one will result in an increase of the total binder (cement plus fly ash) content, and in the present test series the effects of using k = 0.4 and 0.8 are investigated.

The water-to-cement ratio, w_0/C, is calculated by rearrangement of Eq. 1 as

$$\frac{w_0}{C} = \frac{w_0}{C_{equ}} \cdot \left(1 + k \cdot \frac{FA}{C}\right) \qquad (2)$$

All tests presented here are produced with concrete based on the Swedish cement type Anläggningscement Std P Degerhamn CEM I 42.5 N BV/SR/LA, produced by Cementa AB aimed for civil engineering structures, and the fly ash is black coal fly ash from Rostok, Poland, produced by Warnow-Füller. It fulfills demands according to SS-EN 450 and is allowed for concrete production according to demands stated by SS-EN 206.

Air entraining agent has been included in all mixes. In the numerical evaluation, the amounts of the constituents have been slightly revised with respect to the measured air content.

Table 1 Mix compositions for performed heat development and strength growth tests.

Mix No.	*FA/C*	W_0/C_{equ}	*k*	*C* kg/m^3	*FA* kg/m^3
1	0	0.40	-	430	-
2	0.06	0.40	0.4	420	25.2
3	0.11	0.40	0.4	412	45.3
4	0.25	0.40	0.4	391	97.8
5	0.40	0.40	0.4	370	148
6	0.06	0.40	0.8	410	24.6
7	0.11	0.40	0.8	395	43.5
8	0.25	0.40	0.8	358	89.5
9	0.40	0.40	0.8	326	130
10	0	0.55	-	370	-
11	0.06	0.55	0.4	361	21.7
12	0.11	0.55	0.4	354	38.9
13	0.25	0.55	0.4	337	84.2
14	0.40	0.55	0.4	319	128
15	0.06	0.55	0.8	353	21.1
16	0.11	0.55	0.8	340	37.4
17	0.25	0.55	0.8	308	77.0
18	0.40	0.55	0.8	280	112

2.2 Heat development

Due to chemical reactions between cement and water, heat is generated during the hardening process of concrete. The heat development can be determined with calorimetric methods and in this paper a semi-adiabatic method has been used. Cylinder samples of concrete have been cured under semi-adiabatic conditions, and the temperature in the samples has been registered. After about two weeks the specimen has been heated, still situated inside the semi-adiabatic equipment, and the cooling phase has been registered. The exchange of heat with the surrounding during the hydration phase, expressed by the so called heat cooling ratio, is then possible to calculate. This is realized to be able to compensate for the loss of heat during the test period, see further Ekerfors and Jonasson (2000).

All tested mixes are evaluated regarding generated heat for the total binder content, expressed as a function of temperature equivalent time, t_e, by Eq. 3 from Jonasson (1984).

$$W_B = \frac{W_{tot}}{B} = W_U \cdot exp\left[-\lambda_1 [ln(1+\frac{t_e}{t_1})]^{-\kappa_1} \right] \qquad (3)$$

where W_B = generated heat by weight of binder [J/kg], B = binder content, here the sum of cement and fly ash content [kg/m^3], W_{tot} = generated heat at testing [J], W_U [J/kg], t_1 [h], and κ_1 [-] are individual fitting parameters valid for each tested mix. λ_1=1 [-] has been used for all evaluations because it is not an uncoupled parameter. For the denotation t_e, see further Eq. 5.

2.3 Strength Growth

The strength development in concrete is influenced by the temperature. By curing in different temperatures and testing the compressive strength, it is possible to determine the effect of temperature on the strength development and to determine the maturity function.

Concrete cubes of 100x100x100mm are stored in three different water temperatures: 5°, 20° and 35°, respectively. The concrete temperature is registered continuously and the strength development is studied by testing the compressive strength at four occasions between 8 and 168 h after casting. Additional cubes are cured under water in 20°C to determine the 28-day and 91-day compressive strength. All cubes are tested wet.

The strength growth for all tested mixes is evaluated with according to Eq. 4, where the lower formula is proposed by Kanstad et al (1999). The upper formula for $t_e \le t_A$ is intended for very early age strength estimations to be able to assess trowelling and slipform actions, buy here no measurements are performed in this region.

$$f_{cc}(t_e) = \begin{cases} (t_e / t_A)^{n_A} \cdot f_A & \text{for } 0 \le t_e < t_A \\ exp\left[s \cdot \left(1 - \sqrt{\dfrac{672 - t_S}{t_e - t_S}} \right) \right] \cdot f_{28} & \text{for } t_e \ge t_A \end{cases} \qquad (4)$$

where f_{28} [MPa], s [-], t_S [h], t_A[h] and n_A [-] are fitting parameters. The magnitude of f_A [MPa] is calculated using the lower formula in Eq. 4 for $t_e = t_A$.

2.4 Maturity Function

The properties of the hardening concrete are here based on the maturity concept expressed by the temperature equivalent time, t_e, described by Jonasson (1994) as

$$t_e = \int_t \beta_T \cdot dt \qquad (5)$$

where t = time [s, h or d], β_T is the factor for temperature sensitivity, often called the maturity function, which can be expressed (Freisleben Hansen and Pedersen, 1977, and Byfors, 1980) by:

$$\beta_T = \begin{cases} exp\left[\theta \cdot (\frac{1}{293} - \frac{1}{T+273}\right] & \text{for T > -10 } ^\circ C \\ 0 & \text{for T} \leq \text{-10 } ^\circ C \end{cases} \tag{6}$$

where (Jonasson, 1984)

$$\theta = \theta_{ref} \cdot \left(\frac{30}{T+10} \right)^{\kappa_3} \tag{7}$$

where θ_{ref} [K] and κ_3 are fitting parameters according to best fit with test data.

3 NUMERICAL TENDENCY MODELS

3.1 Maturity function

For the tested mixes, Nos. 1-18, the maturity function has been evaluated by analyzing the results from the strength development at varying temperature according the procedure described in Ekerfors and Jonasson (2000). No significant variation between the tested mixes regarding the θ-value could be found. It is thus concluded that the variation is randomly spread irrespectively from fly ash content or w_0/C ratio. All tested mixes are represented by the same maturity function plotted in Figure 1 by the use of Eq. 7 with the following numerical values:

$$\text{For all concretes} \begin{cases} \theta_{\text{ref}} = 3870 \quad \text{K} \\ \kappa_3 = 0.57 \end{cases}$$

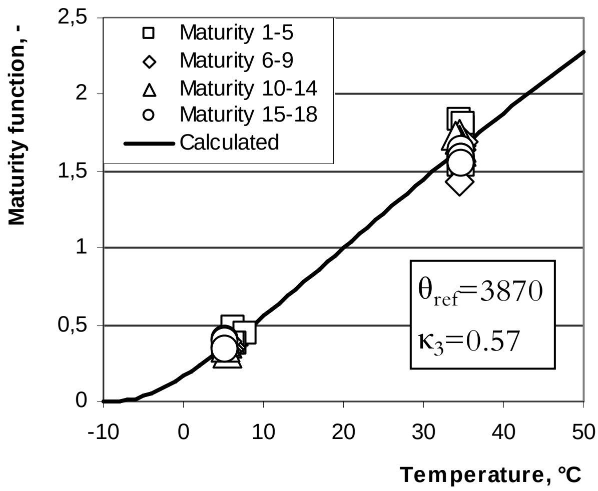

Figure 1 Maturity function valid for tested mixes 1-18.

3.2 Heat development

Mixes 1-18 are individually evaluated in accordance with Eq. 3, and Figure 2 shows the evaluation for mix 1 and mix 11. It can be concluded that Eq. 3 satisfactory describes the hydration process. Calculations can recreate measured temperatures within approximately ± 1°C.

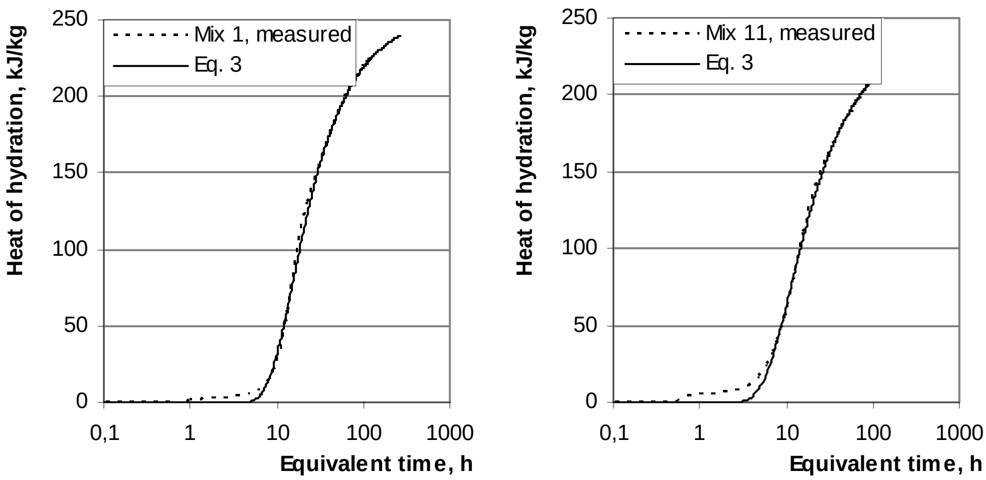

Figure 2 Individual evaluation of the heat of hydration for mix 1 and mix 11.

Tendencies regarding the heat of hydration due to w_0/C ratio and fly ash content have been evaluated. In the tendency model the effect on the hydration heat is assumed to be separated into effects of the w_0/C ratio and of the fly ash content, respectively. This assumption makes it easier to choose which formula to be used to model different observed effects in a consistent way.

The subsequent relations, Eqs. 8 – 14, describing the heat of hydration, with parameters for use of Eq. 3, have shown to give a satisfactory agreement with the tested heat developments for the concrete mixes 1- 18.

$$W_U = W_{ref} \cdot \gamma_w \quad (8)$$

$$\kappa_1 = \kappa_0 \cdot \gamma_1 \quad (9)$$

with the following numerical expressions:

$$W_{ref} = 275 - 20 \cdot exp\left[-\left(\frac{w_0 / C}{0.65}\right)^2\right] \quad \text{[kJ/kg]} \quad (10)$$

$$\gamma_w = 1 - 0.69 \cdot \frac{FA}{C} \quad (\geq 0.3) \quad (11)$$

$$\kappa_0 = 1.65 + 0.35 \cdot exp\left[-\left(\frac{w_0 / C}{0.55}\right)^7\right] \quad (12)$$

$$\gamma_1 = 1 + 0.2 \cdot \left(1 - exp\left[-\left(\frac{FA/C}{0.8} \right)^2 \right] \right) \quad (13)$$

$$t_1 = 8 + 2.7 \cdot exp\left[-\left(\frac{w_0/C}{0.54} \right)^{25} \right] \text{ [h]} \quad (14)$$

In Figure 3 and Figure 4 the individually evaluated W_U, t_1 and κ_1 are plotted versus the, for use in the tendency model, calculated values for mixes 1-18. The parameters evaluated in the presented model show satisfactory agreement when compared to each individual evaluation.

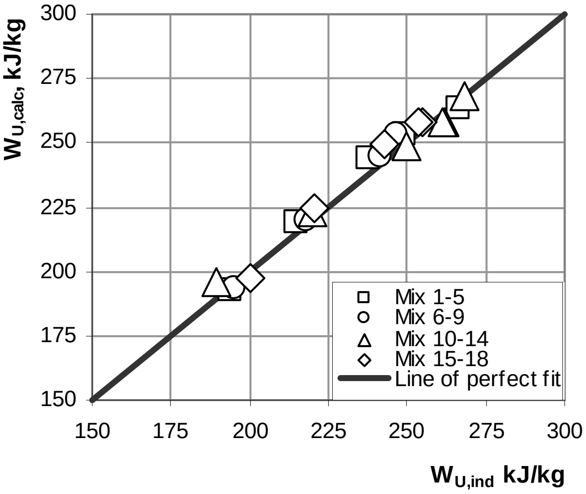

Figure 3 Calculated $W_{U,calc}$ plotted versus the individually evaluated $W_{U,ind}$ for mixes 1-18.

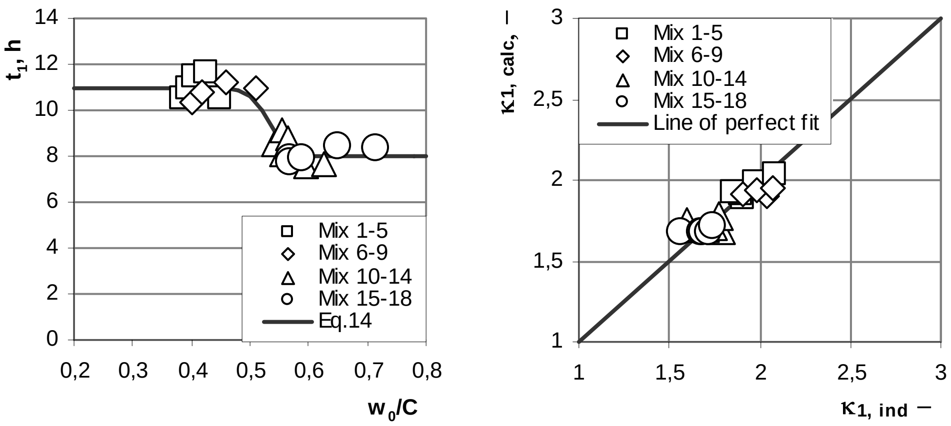

Figure 4 Left figure: Calculated t_1 plotted versus the water-to-cement ratio and right figure: κ_1 plotted versus the individually evaluated for mixes 1-18.

Figure 5 is showing the predicted heat of hydration calculated with the suggested tendency model and it is compared to the measured for mixes 1-5. It can be concluded that the heat of hydration acceptably can be described with the presented model.

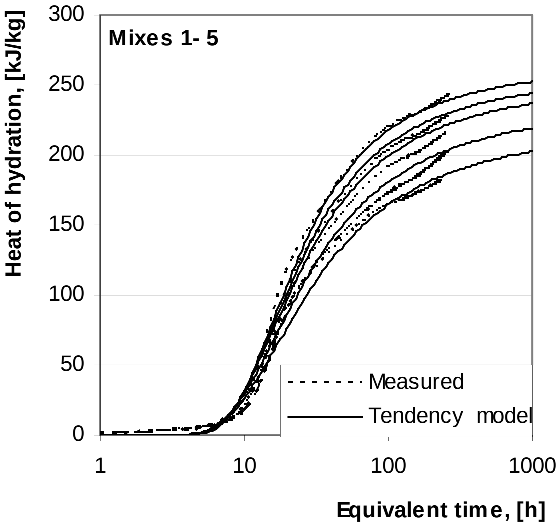

Figure 5 Measured heat of hydration in comparison to the, with the tendency model calculated, heat of hydration for mixes 1-5.

3.3 Strength growth

The individual evaluation regarding the strength growth for mixes 1-18 has been performed with Eq. 4. The results for mix 1 and mix 18, the mixes showing the highest and lowest 28-day compressive strength, are presented in Figure 6. It can be concluded that a satisfactory agreement can be received by using Eq. 6 for all tested mixes up to the 28-day compressive strength. Satisfactory agreement can also be received for the 91-day compressive strength for concrete without fly ash. For concrete with higher w_0/C ratio containing fly ash, the increase in compressive strength between 28 and 91 d will be relatively high. This increase can not be described with the use Eq. 6 alone. The 91-day compressive strength is expressed with a separate formula, see further Eq. 25.

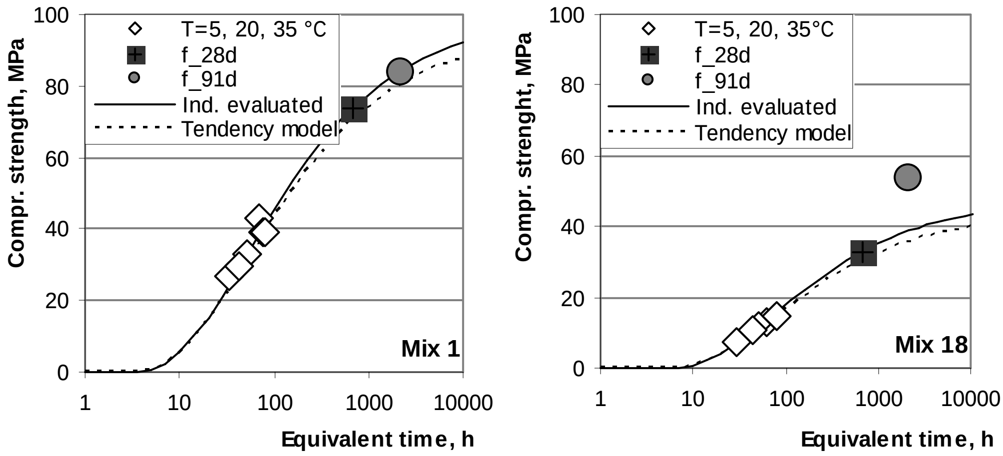

Figure 6 Individually evaluated compressive strength for mix 1 and mix 18 with measured f_{28} = 73.8 MPa and f_{28} = 33.0 MPa, respectively. The dotted line is compressive strength calculated with the tendency model.

Tendencies regarding the strength development due to w_0/C ratio and fly ash content have been interpreted and a numerical tendency model has been established. Analogous with the numerical tendency model for the heat development, the formulation of the strength growth is assumed to be separable regarding effects of w_0/C ratio and fly ash content. The dotted lines in Figure 6 are examples where the proposed tendency model is applied.

The numerical tendency model can be described by:

$$f_{28} = f_{ref} \cdot \gamma_f \qquad (15)$$

$$s = s_0 + (s_1 - s_0) \cdot \gamma_s \qquad (16)$$

with the fitting parameters:

$$f_{ref} = 2700 \cdot exp\left[-\left(80 \cdot \frac{w_0}{C} \right)^{0.378} \right] \text{ [MPa]} \qquad (17)$$

$$\gamma_f = 1 + 0.35 \cdot \frac{FA}{C} \quad (\leq 1.2) \qquad (18)$$

$$s_0 = 0.41 - 0.14 \cdot exp\left[-\left(\frac{w_0/C}{0.5} \right)^5 \right] \qquad (19)$$

$$s_1 = 0.36 \qquad (20)$$

$$\gamma_s = 1 - exp\left[-\left(\frac{FA/C}{0.21} \right)^2 \right] \qquad (21)$$

$$t_S = 3 + 2.5 \cdot \left(1 - exp\left[-\left(\frac{FA/C}{0.3}\right)^2\right]\right) \quad \text{[h]} \qquad (22)$$

$$t_A = 1.5 \cdot t_S \quad \text{[h]} \qquad (23)$$

$$n_A = 3 \qquad (24)$$

In Figure 7 and Figure 8, the measured f_{28} and individually evaluated s and t_S are plotted versus the calculated values using the tendency model for mixes 1-18.

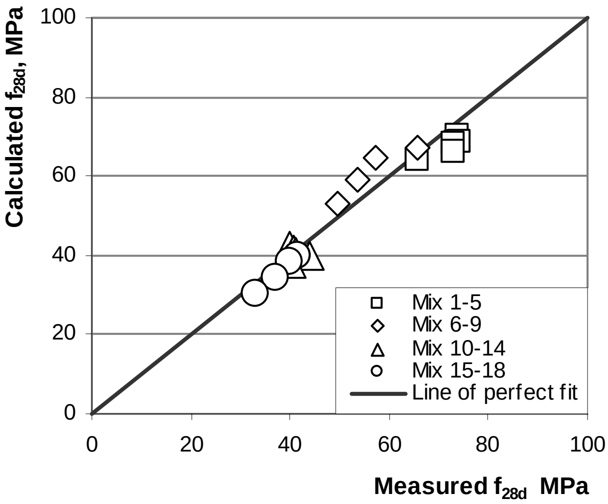

Figure 7 Calculated f_{28} plotted versus the measured for mixes 1-18

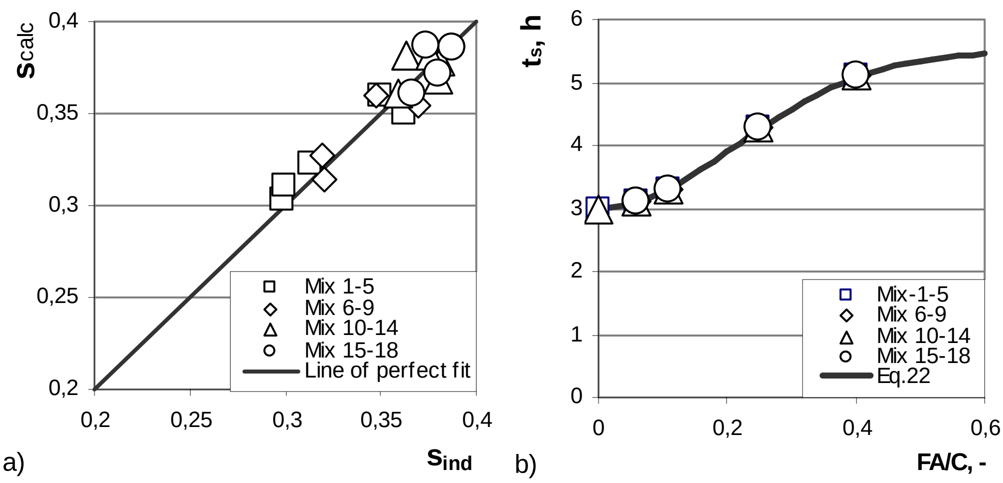

Figure 8 a)Calculated s plotted versus the individually evaluated for mixes 1-18, and b) t_s as a function of the fly ash content.

The increase of 91-days compressive strength, an observed effect of higher fly ash contents, is not reflected by Eq. 4. The needed additional formulas to catch this strength rise are expressed as

$$f_{91} = f_{91,ref} \cdot \gamma_{91} \tag{25}$$

$$\gamma_{91} = 1 + \gamma_{max} \cdot \lambda_{FA} \tag{26}$$

$f_{91,ref}$ is calculated with Eq. 4 for t_e =91d =2184h. γ_{91} is a parameter larger than one, which will increase for increased the fly ash content.

The 91-day compressive strength is described with numerical parameters according to:

$$\gamma_{max} = 0.42 \cdot \left(1 - exp\left[-\left(\frac{w0/C}{0.54}\right)^5\right]\right) \tag{27}$$

$$\lambda_{FA} = 1 - exp\left[-\frac{FA/C}{0.16}\right] \tag{28}$$

A comparison between individually evaluated and calculated enlargement factors for the 91-day compressive strength is illustrated in Figure 9. It can be noticed that for mix 18 (=highest γ_{91} value in Figure 9), the increase is almost 40% in comparison with the value only using Eq. 4. The model is chosen to be most accurate for higher fly ash contents, as small amounts of fly ash showed a higher variation in the tested results, see the lower-left part of Figure 9.

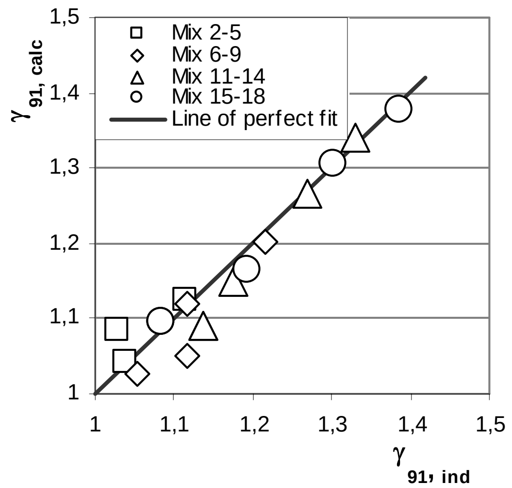

Figure 9 Calculated γ_{91} values using the tendency model plotted versus individual evaluated values

4 THEORETICAL STUDY OF THE EFFECT FROM DIFFERENT FLY ASH CONTENTS

4.1 Choice of structure and mix composition

Calculations are performed on an assumed civil engineering structure, Figure 10. It comprises a bottom slab, walls and a top slab. Calculations are performed in section A of the top slab with and in section B of the wall. The top slab is chosen to be 0.8m thick and the walls are selected to be 0.7m thick.

The calculation examples are based on two types of concrete with w_0/C_{equ} = 0.4 and 0.5, respectively. For w_0/C_{equ} = 0.4 the reference mix with 0% fly ash contains 420 kg/m^3 Portland cement with a required 28-days compressive strength of 45MPa. For w_0/C_{equ} = 0.5 the reference mix with 0% fly ash contains 400 kg/m^3 with a required 28-days compressive strength of 35MPa.

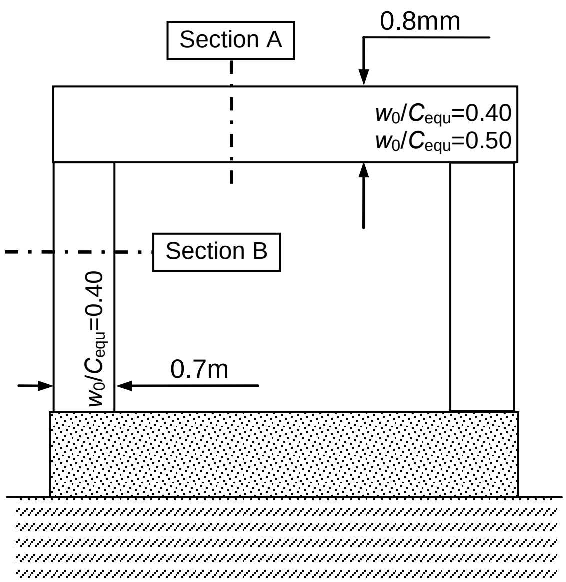

Figure 10 Assumed civil engineering structure for the heat and strength development calculations at different temperatures and varying fly ash contents.

Cement is replaced by fly ash in three amounts, 11%, 25%, and 40% by weight of the cement content. The sum of cement and fly ash, $C + FA$, has been kept constant at the same amount as in the reference mix, i.e. 420kg/m^3 and 400 kg/m^3, respectively, with an efficiency factor of 0.4. Material parameters for the usage of the computer program ConTest (2008) are determined in accordance with the tendency model presented in section 3. The mix composition and the calculated heat and strength parameters are presented in Table 2.

Table 2 Mix composition and calculated material parameters used in computer programConTest (2008).

	0% Fly ash		11% Fly ash		25% Fly ash		40% Fly ash	
w_0/C_{equ}	0.40	0.50	0.40	0.50	0.40	0.50	0.40	0.50
C [kg/m^3]	420	400	378	360	336	320	300	286
w_0 [kg/m^3]	168	200	157	189	149	175	140	165
FA [kg/m^3]	0	0	42	40	84	80	120	114
k [-]	-	-	0.4	0.4	0.4	0.4	0.4	0.4
W_U [J/kg]	261305	263932	241896	244430	217096	219474	190401	192569
λ_1 [-]	1	1	1	1	1	1	1	1
t_1 [h]	10.70	10.33	10.70	9.76	10.68	8.55	10.64	8.01
κ_1 [-]	1.964	1.86	1.96	1.832	1.97	1.812	1.993	1.809
f_{28} [MPa]	66.3	47.9	64.8	46.5	63.0	44.9	61.1	43.2
s [-]	0.309	0.358	0.327	0.367	0.352	0.365	0.359	0.361
t_S [h]	3	3	3.3145	3.3145	4.2516	4.2416	5.0775	5.0775
t_A [h]	4.5	4.5	4.972	4.9717	6.3774	6.3774	7.6162	7.6162
η_A [-]	3	3	3	3	3	3	3	3
θ_{ref} [K]	3870	3870	3870	3870	3870	3870	3870	3870
κ_3 [-]	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57

The calculated values of f_{28} in Table 2 show that the required strength values, $f_{28} \geq 45$ MPa for $w_0/C_{equ} = 0.4$ and $f_{28} \geq 35$ MPa for $w_0/C_{equ} = 0.4$, are reached for all mixes.

4.2 Results for section A of the top slab

4.2.1. Assumed performance conditions and demanded target values

In section A of the top slab calculations are performed for the conditions illustrated in Figure 11; Formwork made of 25mm wood at the bottom with wind velocity of 1m/s below the formwork; A free surface on the top exposed to air with wind velocity of 5 m/s. Calculations are performed at four different outdoor temperatures; 0, 5, 10 and 15°C, and for two different w_0/C_{equ} ratios, 0.40 and 0.50.

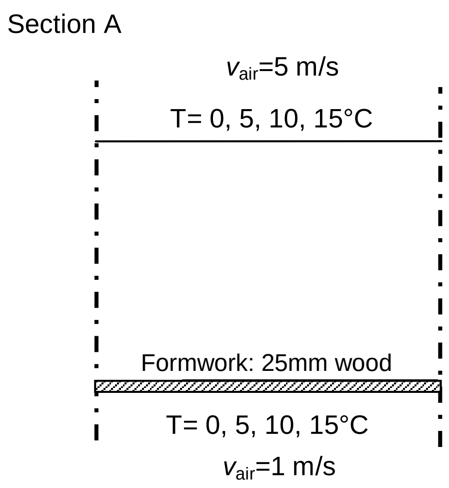

Figure 11 Conditions used in the calculations for section A.

The results are evaluated considering the following assumed demanded values:

- Time when reaching 5 MPa in compressive strength at the top surface, which is employed as the limit for early age frost protection for the actual situation.
- Form removal time regarding the demand of a sufficient average compressive strength of 70 % of the required strength at 28 d.
- Demands on surface moisture curing for T≥10°C until the top surface reaches 50 % of the required strength at 28 d.

The demands on the performance of a concrete structure may be stated in accordance with some code or stated directly by the owner of the building object. However, calculations of the type performed here can answer questions if, when and how any stated demand of the type described here can be fulfilled, and the chosen demands shall only be regarded as an arbitrary set of possible demands. It is usually essential to get information if additional measures are needed or not for a given situation.

4.2.2. Estimation of the risk for early freezing

The risk for early freezing occurs if the concrete freezes before reaching the stated demand of 5MPa compressive strength. To get information to estimate the need for protection against early freezing, it is important to calculate the time needed for the concrete to reach this limit. In springtime or in the autumn, the temperature can reach 10°C during the day, but it can fall below zero during the night. The time needed to reach 5MPa at different fly ash contents for temperatures between 0 and 10°C is plotted in Figure 12. From the figure it is seen that the time to reach 5 MPa is delayed with higher fly ash contents and lower air temperatures. Note that it take about two days to get frost protection using 40 % of fly ash content at 0°C temperature for w_0/C_{equ}=0.40. The time for w_0/C_{equ}=0.50 is further delayed with approximately ten hours. For these cases, probably some measures should be taken to speed up the hydration rate, but this is not studied here.

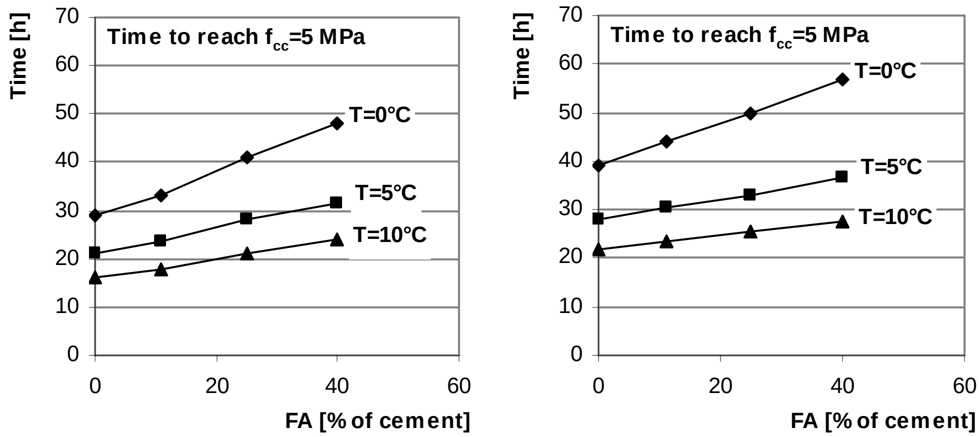

Figure 12 Time needed to reach 5MPa, the demanded limit for protection against early freezing, for different fly ash contents and different outdoor temperatures. Left figure is valid for w_0/C_{equ}=0.40 and right figure is valid for w_0/C_{equ}=0.50

4.2.3. Calculation of form removal times

The predetermined demand to allow formwork removal for the top slab is 70 % of the required 28-days compressive strength, which for this case with f_{28} = 45 MPa means 31.5 MPa, and for f_{28} = 35 MPa the form stripping strength is 24.5 MPa. The calculated times to reach these demanded levels are presented in Figure 13.

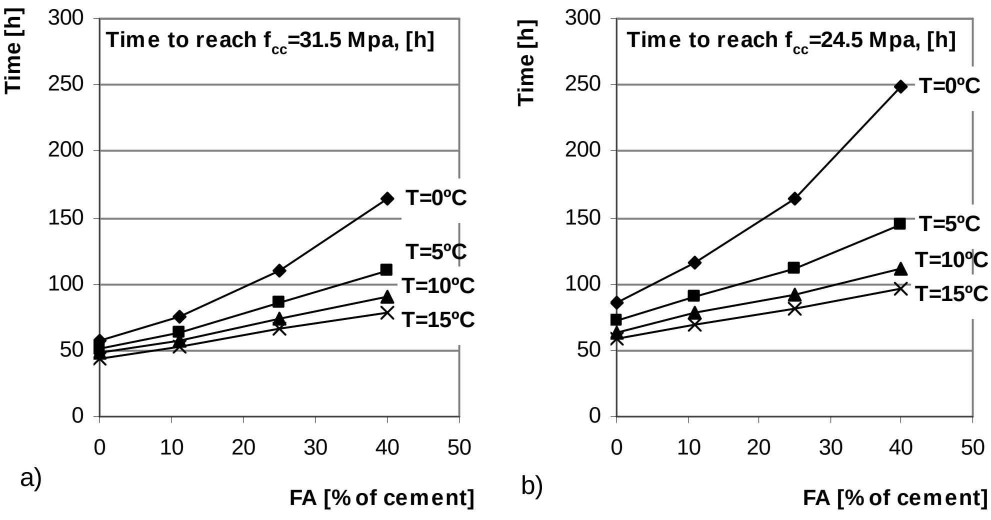

Figure 13 Time needed to reach 70% of required f_{28} for different fly ash contents when the outdoor temperature is 0, 5, 10 and 15°C. a) f_{28} = 45MPa and b) f_{28} = 35MPa.

It can be concluded that the effect of the outdoor temperature on the strength development will significantly increase when the fly ash content increases. In case of 0% fly ash, the time needed to reach 31.5MPa and 24.5MPa will only slightly increase when the outdoor temperature is 0°C in comparison to 15°C. When cement is replaced by 40% fly ash, the time needed to reach demanded form removal time will increase with a factor two if the temperature is 0°C compared to 15°C for $w_0/C_{equ} = 0.40$. For $w_0/C_{equ} = 0.50$, the corresponding time delay is increased about 2.5 times. These delays mean that the use of high fly ash contents in low temperatures should always be completed with analyses to form the basis for decisions how to act.

4.3 Results for section B of the walls

4.3.1. Assumed performance conditions and demanded target values

Calculations for section B in the walls are performed for the conditions illustrated in Figure 14. Formwork made of 25mm wood at both sides exposed to an air wind velocity of 5 m/s. As in the example with the top slab, calculations are performed at four different outdoor temperatures; 0, 5, 10 and 15°C.

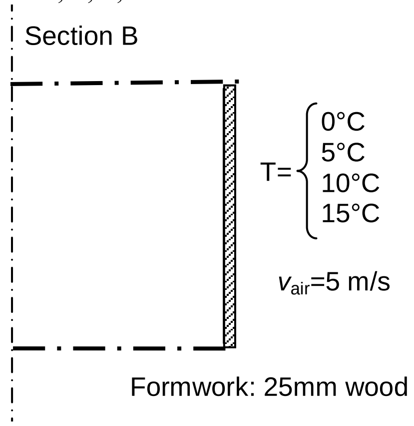

Figure 14 Conditions used in performed calculations for section B

The demand on surface moisture curing is assumed to be the time until 50 % of the required strength is reached at the surfaces. The retained formwork is an accepted alternative to moisture curing, which means that the form removal shall not be performed earlier than the demanded time for moisture curing. However, form stripping might cause high tensile stresses and surface cracking. The recommendation to limit the risk of surface cracking for walls, see Emborg et al (1997), is that the formwork shall not be removed during the first four days. Form removal times for walls will in the calculation example be either four days or when the concrete has reached 50% of required 28-compressive strength.

4.3.2. Calculation of form removal times

The resulting calculated times to reach half the required 28-days compressive strength is presented in Figure 18.

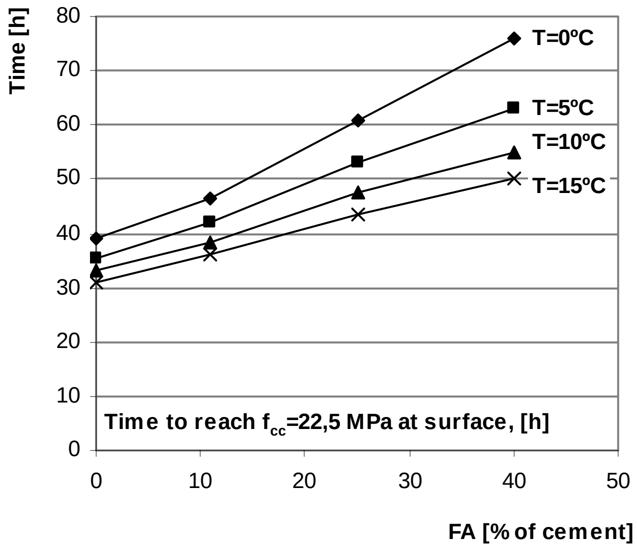

Figure 15 Time needed to reach 0.5·f_{28} at the surface of the wall, which is the demanded limit for moisture curing.

For the analysed wall structure, all calculations performed reach a surface strength higher than 50 % of the required compressive strength within 4 days. So, in relation to the chosen demanded moisture curing condition, the formwork removal demand connected to the risk of surface cracking is here decisive. For other structures and other moisture curing demands the situation might be different.

5 TENDENCY MODEL APPLIED ON ANOTHER CONCRETE GROUP

5.1 Introduction

The presented tendency model is based on measured data performed on one type of concrete with various fly ash contents. The basic assumption when building the formulas is that the effects of w_0/C ratio and of the fly ash content can be mathematically separated. However, there is an interest in investigation of how the presented model may suit another type of concrete group, but still using the same type of cement and same type of fly ash.

In this section, measured heat development and strength growth for another group of concrete is compared with the presented model.

Three concrete mixes containing 0%, 11% and 25% fly ash has been tested. They are composed according to the values presented in
Table 3, see further paper D, and they are composed with another type of aggregate and with other dosages of superplastiziser in comparison to the 18 mixes that the tendency model is based on.

Table 3 Mix-composition for the new group of tested mixes.

Mix No.	FA/C	w_0/C_{equ}	*k*	C kg/m^3
1	0	0.437	-	400
2	0.06	0.421	0.4	400
3	0.11	0.417	0.4	400

5.2 Heat of hydration

In Figure 16, the measured heat of hydration is plotted together with the results calculated with the presented tendency model, see dotted lines. A difference between measured data and calculated is obtained.

For all of the three tested mixes there are two main tendencies concerning heat of hydration between the measured data and the tendency model; 1) the total heat of hydration per kg binder is increased, and 2) the reduction in heat, followed by an increased content of fly ash, is less pronounced. By adjusting the fitting parameters in the two formulas that expresses the effect from w_0/C ratio and the fly ash content, Eqs. 10 and 11, the tendency model is adjusted to describe the behaviour for the new concrete group.

$$W_{ref} = 283 - 20 \cdot exp\left[-\left(\frac{w_0 / C}{0.65}\right)^2\right] \qquad \text{(10-ajd)}$$

and

$$\gamma_w = 1 - 0.23 \cdot \frac{FA}{C} \quad (\geq 0.7) \qquad \text{(11-adj)}$$

The material related behaviour behind this phenomenon is not known, but it can very easily, and for a few adjustments, be mathematically expressed for further heat calculations.

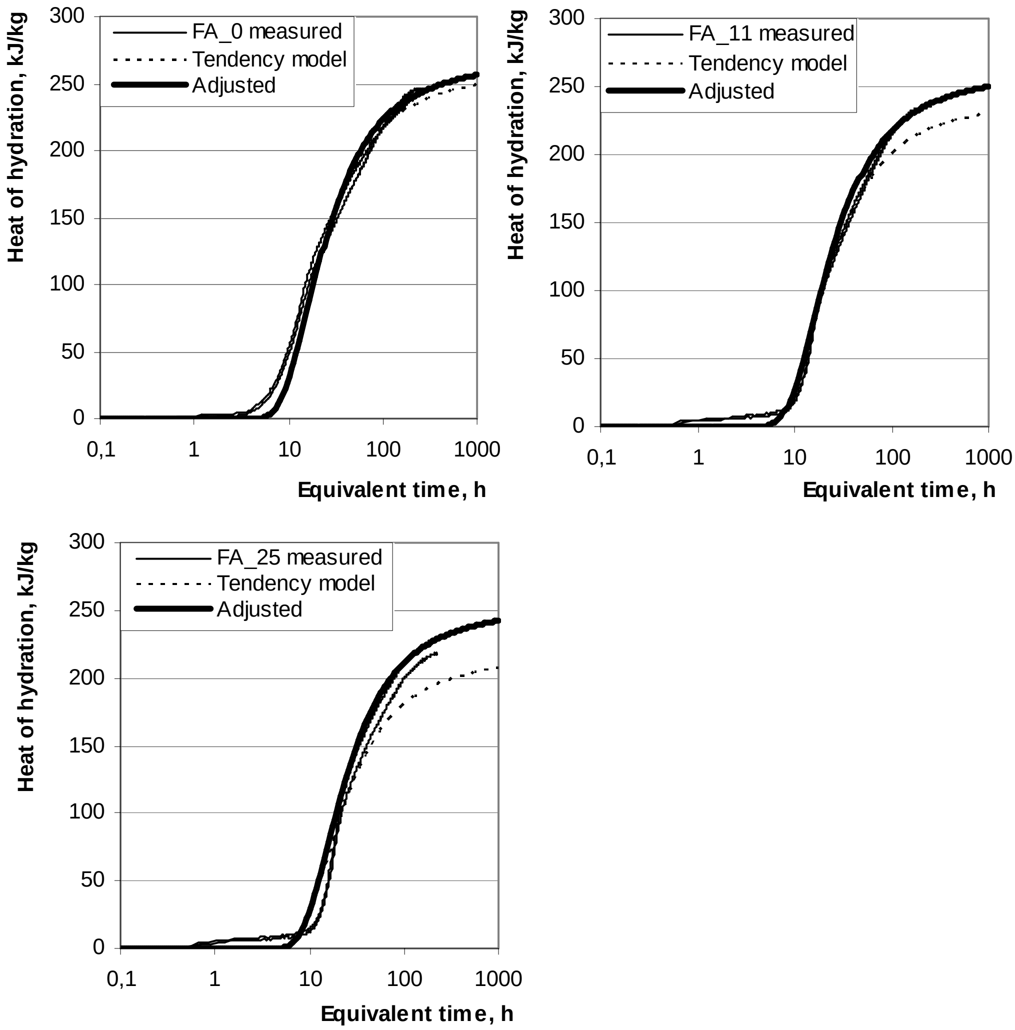

Figure 16 Measured heat of hydration plotted together with calculated by the presented tendency model and the adjusted tendency model. By a few adjustments, the model can be applied on other types of concrete.

5.3 Strength growth

In Figure 17, the measured compressive strength growth is plotted in comparison with calculations using the presented tendency model (dashed lines) and after adjustments (solid lines). The new tested concrete group is showing a lower 28-day compressive strength than calculated and the strength growth is faster in the beginning. These two phenomena can be adjusted by Eqs. 17 - 20 expressed by

$$f_{ref} = 2700 \cdot exp\left[-\left(80 \cdot \frac{w_0}{C} \right)^{0.392} \right] \quad \text{[MPa]} \qquad \text{(17-adj)}$$

$$\gamma_f = 1 + 0.94 \cdot \frac{FA}{C} \qquad (\leq 1.4) \qquad (18\text{-adj})$$

$$s_0 = 0.29 - 0.10 \cdot exp\left[-\left(\frac{w_0/C}{0.5} \right)^5 \right] \qquad (19\text{-adj})$$

$$s_1 = 0.30 \qquad (20\text{-adj})$$

By introducing these adjustments the adjusted tendency model can be used for this new type of concrete group, and all necessary data to be able to perform further analyses of heat and strength developments using different amounts of fly ash.

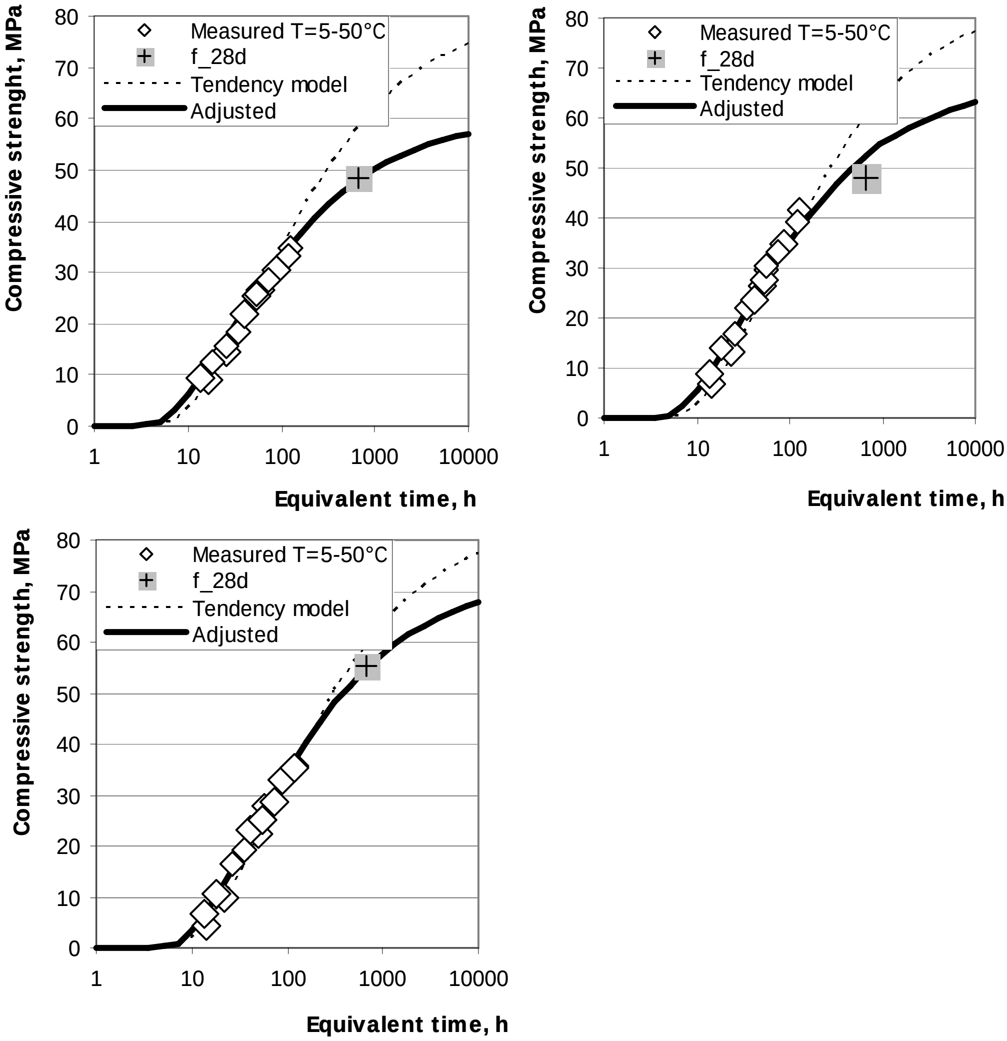

Figure 17 **Measured compressive strength for temperature 5, 20, 35 and 50°C compared to the calculated with the tendency model and calculated by the adjusted model.**

5.4 Concluding remarks

The three additional tested concrete mixes are composed from other types of aggregate materials, and it could be concluded that the presented model did not describe the behavior sufficiently. However, by a few adjustments the model is applicable on the new group of concrete mixes. This indicates that the basic structure of the presented tendency model may be useful for other types of concretes containing different amounts of fly ash.

Since the tendency model is based on formulas expressing the effect of the water-to-cement ratio and of the amount of fly ash as partial factors, it facilitates the possibility to trace where adjustments probably shall be performed. The new tested concrete group and its correlation to the presented tendency model showed a systematic deviation, which easily directed the necessary adjustments to a limited number of parameters. Hereby, a few tests were used to fully describe the behavior for a new group of concrete for further use in strength and heat calculations. However, to be able to extend this statement into a general situation analyzing different amounts of fly ash, a lot more testing and checking have to be performed.

6 CONCLUSIONS

- The presented numerical tendency model is a useful tool for estimating heat and strength development when fly ash is added in varying amounts. The model is based on the effect from w_0/C ratio and fly ash content in relation to cement content.
- According to the performed calculations, any replacement of cement with fly ash will significantly influence the young concrete properties. The effect on delayed strength growth increases with the increased amount of fly ash and will also increase for lower temperatures. In addition, the effect from fly ash increases at higher water-to-cement ratios.
- The suggested model is based on a test series where all parameters except the w_0/C ratios and fly ash content has been constant. It has been concluded that the suggested model can not directly be applied on concrete composed from other types of material. However, with a few additional tests and adjustments in the tendency model, it has been shown to be applicable on another concrete type with sufficient agreement.
- The suggested model is not a general numerical model valid for any type of concrete. To establish a more general model tests have to be performed studying all parameters that can effect the heat and strength development. For a given type of cement and a given type of fly ash, such additional parameters may be type and dosage of superplastiziser and aggregate type.

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Paper D

Estimation of the Risk for Early Thermal Cracking for SCC Containing Fly Ash

by Sofia Utsi and Jan-Erik Jonasson

ESTIMATION OF THE RISK FOR EARLY THERMAL CRACKING FOR SCC CONTAINING FLY ASH

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Abstract

Cracking of concrete during the hardening phase must be avoided in order to minimize the risk of durability problems in the future, such as corrosion risk of the reinforcement, water tightness and damages according to frost. Estimation of the risk of early age cracking requires knowledge of the combined effects from temperature development and mechanical behaviour during the hydration.

In the present paper, the influence from fly ash on the young concrete behaviour has been investigated. The concrete is based on a Swedish cement aimed for civil engineering structures, and the fly ash is of class F. A comparison of crack risks between concrete containing fly ash in different amounts with concrete without fly ash is presented. Also one earlier tested concrete containing limestone filler is considered.

The fly ash was added to replace a part of the aggregate, which gives a higher heat evolution. However, a numerical stress analysis showed that the risk for early age through cracking for a typical civil engineering structure is significantly decreased for the mixes containing fly ash. In case of fly ash added to concrete by a partial replacement of cement, the crack risk will probably be further decreased.

The estimated risk for surface cracking on a self-balancing wall or slab was not improved by an addition of fly ash. It is probably an effect of the increased heat development, which most likely compensates the positive effect of the increased early-age creep for concrete containing fly ash. If the heat evolution decreases when cement is partly replaced with fly ash, the use of fly ash might reduce the risk of surface cracks.

1 INTRODUCTION

1.1 Young concrete behaviour

Civil engineering structures are often massive constructions using concrete with high strength and low water to powder ratios. The combination of massive structures and high cement contents may cause undesired cracks during the hydration period. Civil engineering structures are often exposed to harsh environments with an expected service life of up to 100 yrs. Estimations of cracking risks during the hardening phase must thus be included in the design process in order to minimize the risk of durability problems in the future, such as corrosion risk of the reinforcement, water tightness and damages according to frost. The assessment for low crack risks includes decisions regarding necessary measures on the working site and also an evaluation of the mix composition and its heat and mechanical properties during hydration. Young concrete is here defined as concrete from casting and approximately the subsequent first month.

Hydration in concrete is an exothermic chemical reaction. A few hours after the concrete have been mixed the reaction between water and cement starts to generate heat. However, the concrete temperature rise is not uniform as the surface of the structure is affected by environmental conditions. A hardening concrete that is free to deform during the expansion and subsequent contraction phase during the hydration process will not be induced by stresses. But in practice, different parts of concrete structures are always restrained to varying levels of degree. The primary interest is whether or not these induced stresses will lead to cracking.

Estimation of the risk of early age cracking due to hydration requires knowledge of the hardening concrete. The risk for thermal cracking in young concrete is often interpreted regarding the stress or strain, where the risk for cracking is related to the tensile strength or the tensile failure strain. The stress and strain development in young concrete is, according to Emborg and Bernander (1994), mainly a function of four dominant factors:

Temperature development in the newly cast concrete: Is described by the heat of hydration and is mainly a function of the geometry of the structure, the cement type and content, and the environmental conditions.

The degree of restraint forces: Is defined as the possibility for the structure containing the newly cast concrete to deform during hydration.

The mechanical behaviour of the young concrete: The mechanical behaviour of young concrete that is of importance for the stress analysis are: strength development in varying temperature, the shrinkage, the thermal dilation, the viscoelastic behaviour and the non-linear stress-strain behaviour at high tensile stresses.

The temperature of adjoining structures: The size of the adjoining structure at time of casting of the new concrete is, for a structure free to deform, determined by its temperature. If the temperature of the adjoining structure is larger than the environmental temperature, it means, compared with a structure in temperature equilibrium with the environment, a reduction of cracking risks in the newly cast concrete.

In this paper properties of young concrete are tested and evaluated for concretes containing different amounts of fly ash. This covers necessary data to do crack risk analysis, and for some typical cases calculated crack risks are presented.

1.2 The effect of fly ash on young properties

Fly ash is an industrial by-product from coal-fired power stations and it has been proven to be a sufficient concrete making material when replacing cement in varying amounts. It comprises spherical glassy particles in the size of cement, approximately 1 to 150 μm. The spherical shape has been proven to improve the workability of fresh concrete and the water content needed for a certain workability can be reduced (Davis et al., 1937, Berry and Malhotra, 1980, Lane and Best., 1982, Bilodeau and Malhotra, 2000).

Fly ash is a pozzolanic material, which means that it reacts with the calcium hydroxide $Ca(OH)_2$ that is produced when cement reacts with water. When fly ash reacts with $Ca(OH)_2$, calcium silicate hydrate (CSH) is formed, which will result in an increase of the content of the durable material (CSH). Fly ash is often used in concrete because of its excellent concrete making properties, especially in the fresh phase where retained workability can be received at decreased water content, e.g. Cannon (1968), Lane (1983). However, any incorporation of a pozzolanic material in concrete will influence the young and mature concrete properties. To ensure that sufficient concrete performance can be received, it is essential to understand how an incorporation of fly ash influences important concrete properties.

All tests presented here are produced with concrete based on the Swedish cement type Anläggningscement Std P Degerhamn CEM I 42.5 N BV/SR/LA, produced by Cementa AB aimed for civil engineering structures, and the fly ash is black coal fly ash from Rostok, Poland, produced by Warnow-Füller. It fulfills demands according to SS-EN 450 and is allowed for concrete production according to demands stated by SS-EN 206.

1.3 Scope and Objectives

Fly ash in concrete has not been commonly used in Swedish concrete production, mainly because of the lack of national produced fly ash aimed for usage in concrete. However, there is an increased interest among concrete producers to use fly ash in concrete, either to replace some of the cement content or as a partial replacement of aggregate with the aim to increase the total paste content, which is one possible way of composing a self-compacting concrete.

The main objective with the work presented in this paper has been to investigate the effect from fly ash on the young concrete behaviour. Knowledge of the combined effect of temperature development and mechanical behaviour during the hydration period makes it possible to perform a stress analysis, and on this account the risk of thermal cracking can be estimated. The paper includes a comparison of the crack risk between concrete containing fly ash in different amounts with concrete without fly ash and with one earlier tested concrete containing limestone filler. This is done both directly from the tests as well as by analysis for some typical structural situations.

In the present investigation fly ash is added by a partial replacement of the aggregate; with the aim of increasing the total paste content as an action to produce a self-compacting concrete. This will result in an increase of the total binder content.

The tests have been evaluated in accordance with earlier established numerical models for further use in existing computer programs to realize crack risk analysis for arbitrary structural situations.

2 LABORATORY TESTS

2.1 Material properties and test program

Fly ash contributes to the cement reaction and calcium silicate hydrate products (CSH) are formed. The contribution of fly ash and other mineral additives with respect to an equivalent water-to-cement ratio, w_0/C_{equ}, is generally calculated as

$$\frac{w_0}{C_{equ}} = \frac{w_0}{\left(C + k_{FA} \cdot FA + k_{SF} \cdot SF + k_{Sl} \cdot Sl\right)} \qquad (1)$$

where w_0 = mixing water content [kg/m^3], C_{equ} = equivalent cement content [kg/m^3], C = cement content [kg/m^3], FA = fly ash content [kg/m^3], SF = silica fume content [kg/m^3], Sl = Slag content [kg/m^3], and k_{FA}, k_{SF} and k_{Sl} are efficiency factors with respect to the additive in question [-].

Values of the efficiency factors as well as maximum allowed contents of mineral additives are regulated in recommendations and standards.

When adding fly ash, it can be performed in different ways:

1. Exchange cement with fly ash by weight on a 1:1 basis
2. Exchange parts of the cement and parts of the aggregate
3. Adding fly ash in addition to the cement as a part of the fine aggregate

The tested mixes are designed according to item number three, partial replacement of the aggregate. The main reason is that self-compacting concrete contains higher fine grained materials than concrete aimed to be vibrated. Limestone filler is commonly used in self-compacting concrete in Sweden, which is added as a partial replacement of the aggregate to increase the total paste content. The contribution of adding limestone filler to concrete is generally considered as an addition to the powder content calculated as

$$P = C + FA + SF + SL + Fi \qquad (2)$$

where P = powder content [kg/m^3] and Fi = added filler content [kg/m^3].

The tested mixes presented in this paper are chosen to have 0, 11 and 25 % content of fly ash in relation to the cement content, and they are denoted FA_0, FA_11 and FA_25, respectively, see Table 1. These three mixes have the same cement content (C = 400 kg/m^3) and the equivalent water-to-cement ratio is kept constant at 0.42 when using an efficiency factor (k_{FA}) of 0.4.

From tests presented in Hedlund (2000) a SCC mix using limestone filler is chosen as a “normal” SCC reference mix, and it is denoted SCC_Lime in Table 1. The cement content is slightly higher than 400 kg/m^3 and the water-to-cement ratio is slightly lower than 0.42.

Table 1 Mix compositions for tested concretes

Material	FA_0	FA_11	FA_25	SCC_Lime
Cement [kg/m^3]	400	400	400	405
Water [kg/m^3]	168	174	183	158
w_0/C_{equ}	0.42	0.42	0.42	0.39
Fly ash [kg/m^3]	-	44	100	-
Limestone filler [kg/m^3]	-	-	-	175
Admixture [% of binder content]	0.04 Sikament 56	0.8 Sikament 56	0.8 Sikament 56	0.98 Glennium 51
Air entrainment adm. [% of binder content]	0.04 Sika AER	0.04 Sika AER	0.04 Sika AER	0.58 Micro Air
Fine Aggregate [% of tot. Agg. content]	40% 0-4mm	63% 0-4mm 20% 4-8mm	52% 0-4mm 13% 4-8mm	9% 0-2mm 49% 0-8mm
Coarse Aggregate [% of tot. Agg. content]	60% 11-16mm	17% 11-16mm	35% 11-16mm	42% 8-16mm
Air content	4.5%	4.5%	4.5%	3.5%

2.2 Performed tests and theoretical models

Theoretical and experimental methods with the purpose of mapping necessary young concrete properties to be able to realize calculations concerning risks of thermal as well as moisture induced stresses have been derived and evaluated at Luleå university of technology (LTU) during a long period (Emborg, 1989, Jonasson, 1994, Westman, 1999, Hedlund, 2000, Groth, 2000, Nilsson, 2003, Larson, 2003, and Carlswärd, 2006).

The tests performed here are in accordance with an established "standard" procedure at LTU to map properties for usage in temperature and stress calculations. In this paper only the most essential formulas are given to be able to understand the meaning of presented data. For further information, enter the referenced literature.

The following areas have been evaluated based on tests:

Maturity function

The properties of the hardening concrete are expressed in accordance with the so called maturity concept, here applied with the temperature equivalent time, t_e, as the independent parameter. The concept originates from Nurse (1949) and Saul (1951), and it was first introduced in Sweden by Bergström (1953):

$$t_e = \int_t \beta_T \cdot dt \qquad (1)$$

where t = time [s, h or d], β_T is the factor for temperature sensitivity, often called the maturity function, which can be expressed (Freisleben Hansen and Pedersen, 1977, and Byfors, 1980) by:

$$\beta_T = \begin{cases} \exp\left[\theta \cdot (\frac{1}{293} - \frac{1}{T+273}\right] & \text{for T > -10 } ^\circ C \\ 0 & \text{for T} \leq \text{-10 } ^\circ C \end{cases} \qquad (2)$$

where θ = “activation temperature“ [K] = (formally:) activation energy divided by general gas constant, which here is expressed (Jonasson, 1984) by

$$\theta = \theta_{ref} \cdot \left(\frac{30}{T+10} \right)^{\kappa_3} \qquad (3)$$

where θ_{ref} [K] and κ_3 are fitting parameters according to best fit with test data.

Heat of hydration

Performed test procedures are fully described in Ekerfors (1995) and Ekerfors and Jonasson (2000), and test data are evaluated regarding generated heat for the total binder content, as expressed by Eq. 3 (Jonasson, 1984).

$$W_B = \frac{W_{tot}}{B} = W_U \cdot \exp\left[-\lambda_1 \cdot \left(\ln(1 + \frac{t_e}{t_1}) \right)^{\kappa_1} \right] \qquad (4)$$

where W_B = generated heat by weight of binder as a function of equivalent time [J/kg], B = binder content, here the sum of cement and fly ash content [kg/m^3], W_{tot} = generated heat at testing [J], W_U = ultimate generated heat by weight of binder [J/kg], and λ_1 [-], t_1 [h] and κ_1 [-] are fitting parameters.

Strength growth at variable temperature

The strength growth at variable temperature has been tested according to the procedure described in Ekerfors (1995). The strength growth for all tested mixes is evaluated according to Eq. 5, where the lower formula has been proposed by Kanstad et al (1999). The upper formula for $t_e \leq t_A$ is intended for very early age strength estimations to be able to assess trowelling and slipform actions, buy here no measurements are performed in this region.

$$f_{cc}(t_e) = \begin{cases} (t_e / t_A)^{n_A} \cdot f_A & \text{for } 0 \leq t_e < t_A \\ \exp\left[s \cdot \left(1 - \sqrt{\frac{672 - t_S}{t_e - t_S}} \right) \right] \cdot f_{28} & \text{for } t_e \geq t_A \end{cases} \qquad (5)$$

where f_{cc} = compressive strength as a function of equivalent time [MPa], f_{28} = 28-days compressive strength [MPa], s [-] and t_S [h] are fitting parameters, t_A = (here chosen to be) = 1.5·t_S = equivalent time when shifting from the upper to the lower formula [h], f_A is the compressive strength at $t_e = t_A$, calculated by the lower formula [MPa].

Creep tests
When deformations at loading are measured, the total deformation is the true material parameter. But, in engineering practice it is common to distinguish between "momentaneous" deformation and "creep deformation". This splitting can be done in many different ways and also be adapted to the application in question. As long as the total deformation is in accordance with the measurements it is only a question of how detailed the information is in the time scale. For young concrete and applications with respect to stresses caused by inelastic deformations at variable temperature and moisture state, the "elastic" time duration, Δt_0, is here chosen to be 0.001d (Emborg, 1989 and Westman, 1999). Hereby, the Young's modulus at loading age t_0, $E(t_0)$, can be expressed by

$$E(t_0) = \frac{1}{J(\Delta t_0, t_0)} = \frac{1}{J(0.001, t_0)} \tag{6}$$

where $J(0.001,t_0)$ is the measured deformation 0.001d (≈ 1.5 minutes) after loading [1/Pa], and t_0 = equivalent age at loading [d].

The total deformation, $J(\Delta t_{load}, t_0)$, can now be expressed by

$$J(\Delta t_{load}, t_0) = \frac{1}{E_0(t_0)} + \Delta J(\Delta t_{load}, t_0) \tag{7}$$

where $\Delta l_{load} = t - t_0$ = load duration, [d], $\Delta J(\Delta t_{load},t_0)$ = "creep" part of the total deformation [1/Pa]

The Young's modulus is here expressed, see Larson (2003) by

$$E_c(t_0) = \left[\exp\left\{ s_E \cdot \left(1 - \sqrt{\frac{28 - t_{SE}}{t_0 - t_{SE}}} \right) \right\} \right]^{0.5} \cdot E_{28} \tag{8}$$

where t_0 = equivalent age at loading [d], t_{SE} = equivalent time, where deformations start to create stresses [d], E_{28} = Young's modulus at equivalent time = 28d [GPa], and s_E = shape parameter for the growth of the elastic modulus [-].

With two straight lines in the logarithmic time scale (Larson, 2003) the creep part can be formulated as

$$\Delta J(\Delta t_{load}, t_0) = \begin{cases} a_1 \cdot \log\left(\dfrac{\Delta t_{load}}{\Delta t_0} \right) & \text{for } \Delta t_0 \le \Delta t_{load} < \Delta t_1 \\[2ex] a_1 \cdot \log\left(\dfrac{\Delta t_1}{\Delta t_0} \right) + a_2 \cdot \log\left(\dfrac{\Delta t_{load}}{\Delta t_1} \right) & \text{for } \Delta t_{load} \ge \Delta t_1 \end{cases} \tag{9}$$

where Δt_1 = time duration for the distinct break point in the creep behaviour [d], a_1 and a_2 are inclinations, dependent on the loading ages, in the linear-logarithmic plot of the creep behaviour [10^{-12}/(Pa log-unit)],

Free deformation at variable temperature
The tests are performed with the aim to determine the free deformation of newly cast concrete at variable temperature. The measured deformation is a combined effect of temperature and moisture changes in the concrete. The problem is to separate them into a thermal deformation related to temperature changes and an autogenous deformation not directly dependent on the temperature changes (Bjøntegaard, 2000). Bjøntegaard measured the thermal deformation by a saw-toothed variation of the temperature, and considered the rest part as an "experimentally determined autogenous deformation" valid for the studied mix. This procedure has been used by Bosjnak (2001), Atrushi (2003) and Ji (2008). The evaluation here is done in a similar way without direct measurements of the thermal deformation. The thermal dilation coefficient of hardening concrete is here chosen as a constant, and the rest part is modelled as a maturity related autogenous shrinkage. The evaluation is realized by a fitting technique based on the measured total deformation for a "realistic" (0.7m wall structure) temperature curve. The model is described in Hedlund (2000) and expressed by

$$\varepsilon_{\text{tot}} = \varepsilon_T^o + \varepsilon_{SH}^o \qquad (10)$$

$$\varepsilon_T^o = \Delta T \cdot \alpha_{\text{T}} \qquad (11)$$

$$\varepsilon_{SH}^o = \begin{cases} 0 & \text{for } t_e \le t_{s1} \\ \dfrac{t_e - t_{s1}}{t_{s2} - t_{s1}} \cdot \varepsilon_{s1} & \text{for } t_{s1} < t_e \le t_{s2} \\ \varepsilon_{s1} + \exp\left[-\left(\dfrac{t_{SH}}{t_e - t_{s2}}\right)^{\eta_{SH}}\right] \cdot \varepsilon_{s2} & \text{for } t_e > t_{s2} \end{cases} \qquad (12)$$

where ε_{tot} = the measured strain [-], ε_T^o = the stress free strain related to changes in temperature [-], ε_{SH}^o = the stress free strain not related to changes in temperature [-], ΔT = change in temperature [ºC], α_T = thermal dilation coefficient [1/ ºC], t_{s1} [h], t_{s2} [h], ε_{s1} [-] ε_{s2} [-], t_{SH} [h] and η_{SH} [-] are fitting parameters.

Stress growth at totally restraint conditions
In the Temperature Stress Testing Machine (TSTM), the stress to strength ratio can be determined at totally restraint conditions. Specimens are located in a totally rigid frame and heated in accordance with a "realistic" temperature development, which is calculated with parameters evaluated for the tested concrete mix applied to a 0.7m thick wall at indoor conditions. The induced stresses in the totally restrained concrete

specimen are measured. The test set-up and performance is fully described in Westman (1999). The results from the TSTM test are a combined effect from all parameters that influence the hardening phase under restraint conditions. When comparing measured and calculated stresses, it might be regarded as a "check point" if the evaluated parameters are able to reflect the measured stress development.

If the specimen cracks the stress at failure represents a "structural" tensile strength at the moment of cracking. If a crack does not appear after reaching a peak value in the measured stress, the specimen is forced to cracking, and again the stress at failure represents a structural tensile strength for the tested concrete. The tensile strength is related to the compressive strength according to

$$f_{ct} = (f_{cc} / f_{cc}^{ref})^{\beta_1} \cdot f_{ct}^{ref} \qquad (13)$$

where f_{ct} = tensile strength [MPa], f_{cc}^{ref} = reference compressive strength [MPa], f_{ct}^{ref} = reference tensile strength [MPa}, and β_1 = exponent [-].

The stress-strain curve used in the calculation is illustrated in Figure 1, and α_{ct} denotes the upper limit of the linear stress-strain at 1st loading. Remaining denotations in Figure 1 are: σ = (uniaxial) stress in the concrete [MPa], ε_m = strain related to stresses in concrete (= "material" strain) [-], ε_0 is the strain related to a linear behaviour all the way up to $\sigma = f_{ct}$.

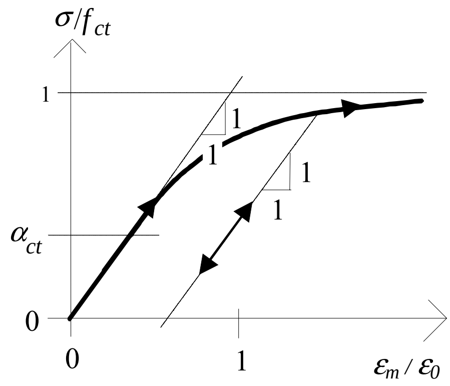

Figure 1 Non-linear stress-strain curve for the concrete in tension.

Finally, in many investigations there has been observed a phenomenon denoted transient creep at variable temperature and humidity (Bažant and Chern, 1985) or stress-induced deformations (Thelandersson, 1987). For young concrete this was introduced in a simplified manner by Jonasson (1994) as

$$\Delta\varepsilon_T = \Delta\varepsilon_T^o \cdot (1 + \rho_T \cdot \frac{\sigma}{f_{ct}} \cdot sign(\Delta T)) \qquad (14)$$

and

$$\Delta\varepsilon_{SH} = \Delta\varepsilon^{o}_{SH} \cdot (1 + \rho_{\varphi} \cdot \frac{\sigma}{f_{ct}} \cdot sign(\Delta T)) \quad (15)$$

where Δ denotes a change associated with a time step (Δt), ε_T = strain related to a temperature variation at a stress level of σ/f_{ct} (≥ 0) [-], σ = stress in the concrete [MPa], ε_{φ} = strain not related to a temperature variation at a stress level of σ/f_{ct} (≥ 0) [-], T = temperature [ºC]

When a discrepancy is observed between the measured (TSTM) and calculated stresses using material related parameters evaluated in accordance with Eqs. 3-14, the modelling interpretation here is to check whether non-zero (>0) values of ρ_T and/or ρ_{φ} are able to give a better fit. Ji (2008) actually measured transient creep both for a young and a mature concrete and presented the results using Eq. 15.

3 TEST RESULTS AND INDIVIDUAL EVALUATIONS

All tested properties, except the maturity function, are individually evaluated according to established numerical models as described in section 2. No tendency model for different concrete properties, as effects of variable fly ash contents, has been established because of the limited amount of performed tests.

All evaluated parameters in accordance with Eqs. 3 – 15 except the relaxation spectra, are presented in Table 2. All the resulting curves from the best-fit procedure are shown in Figures 2 - 7.

3.1 Maturity function

All mixes can be described by the same maturity function, see Figure 2, where the parameters θ_{ref} and κ_3 in Eq. 3 have been evaluated in the tendency model for concrete containing fly ash described in paper C in Utsi (2008).

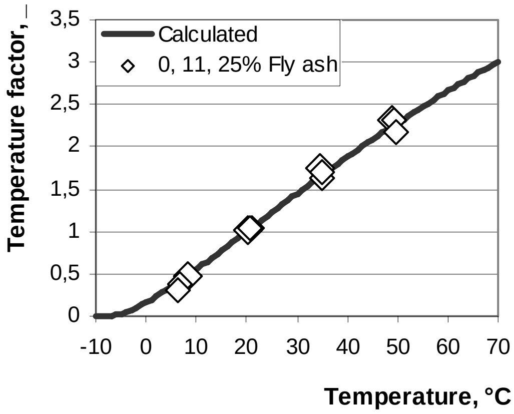

Figure 2 Maturity function for the three tested mixes, where the solid line is calculated with the same parameters as in paper C in Utsi (2008).

Table 2   Evaluated individual parameters

Parameter	FA_0	FA_11	FA_25	SCC_Lime
θ_{ref} [K]	3870	3870	3870	3870
κ_3 [-]	0.57	0.57	0.57	0.57
B** [kg/m^3]	400	444	500	405.8
W_U [J/kg]	316500	277500	257300	368300
λ_1 [-]	1	1	1	1
t_1 [h]	11.7	12.4	12.7	14.3
κ_1 [-]	1.20	1.70	1.91	1.14
Relaxation spectra*	-	-	-	-
s [-]	0.242	0.189	0.273	0.222
t_S [h]	5	8	8	7.2
f_{28} [MPa]	48.2	48.2	55.1	69
t_A [h]	7.5	12	12	10.8
n_A [-]	3	3	3	3
α_T [10^{-6}/°C]	9.4	9.4	9.4	8.4
t_{s1} [h]	6	6	6	6
ε_{s1} [-]	$-35\cdot10^{-6}$	$-50\cdot10^{-6}$	$-50\cdot10^{-6}$	0
t_{s2} [h]	8	8	8	8
ε_{s2} [-]	$-125\cdot10^{-6}$	$-110\cdot10^{-6}$	$-130\cdot10^{-6}$	$-166\cdot10^{-6}$
t_{SH} [h]	2	4	7	6
η_{SH} [-]	1	1	0.7	0.85
f_{cc}^{ref} [MPa]	45.2	45.6	50.6	66.0
f_{ct}^{ref} [MPa]	3.59	3.31	3.96	4.22
β_1 [-]	0.677	0.677	0.677	0.677
α_{ct} [-]	0.75	0.75	0.75	0.75
ρ_T [-]	0	0.6	0.3	0
ρ_φ [-]	0	0	0	0

*)   Not given here, but those interested can contact the writers. See also Figure 5 and table 3.

**) B=C+FA, where C = cement content, and FA = fly ash content.

3.2 Heat of hydration and strength growth

The individual evaluations of the heat of hydration for the tested mixes are illustrated in Figure 3.

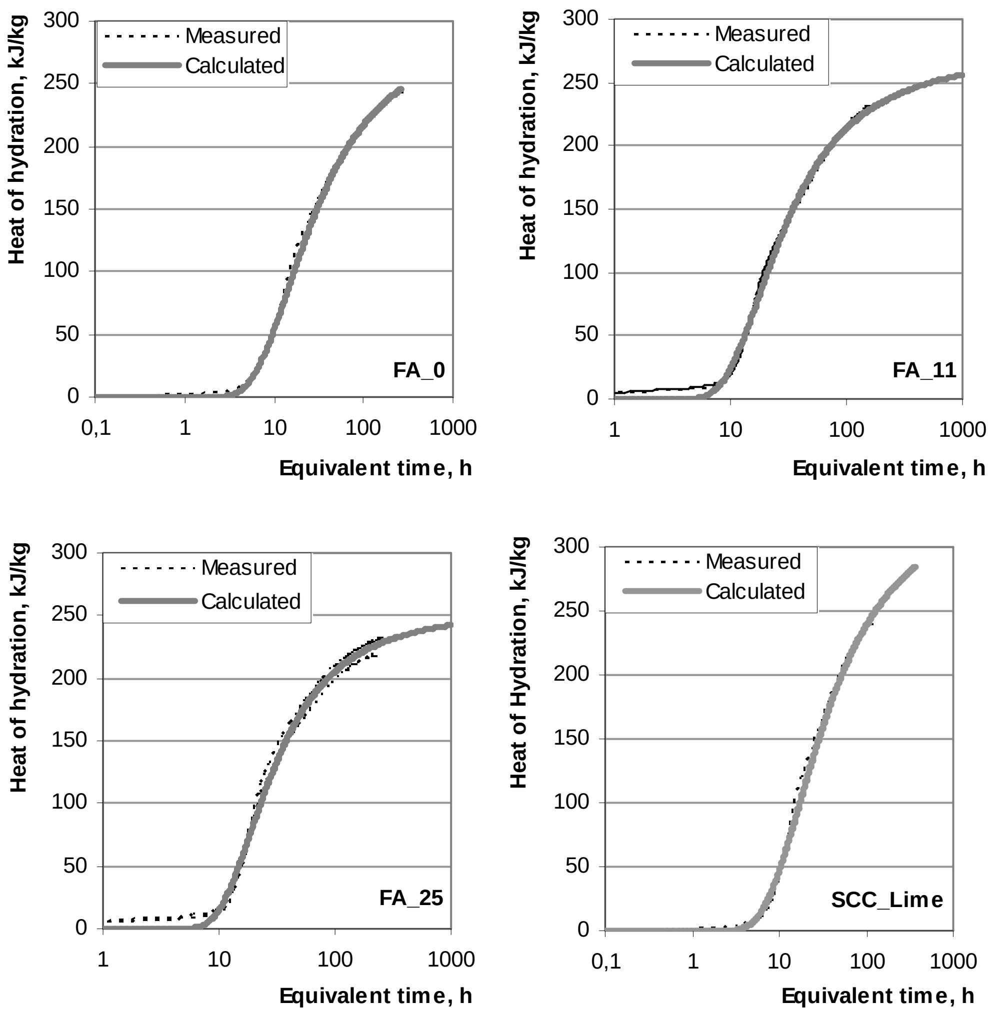

Figure 3 Individual evaluations of the heat of hydration for the tested mixes.

Each individually evaluated strength growth is illustrated in Figure 4. All mixes show a satisfactory agreement with the numerical model. The measured 28-day compressive strength for FA_0 and FA_11 is identical even if the FA_11 contains a larger amount of total binder. FA_25 has a higher 28-day compressive strength, which could be expected because of the increased binder content. The SCC_Lime reaches the highest 28-day compressive strength, which to some extent might be an effect of the slightly lower water-to-cement ratio than the other three mixes.

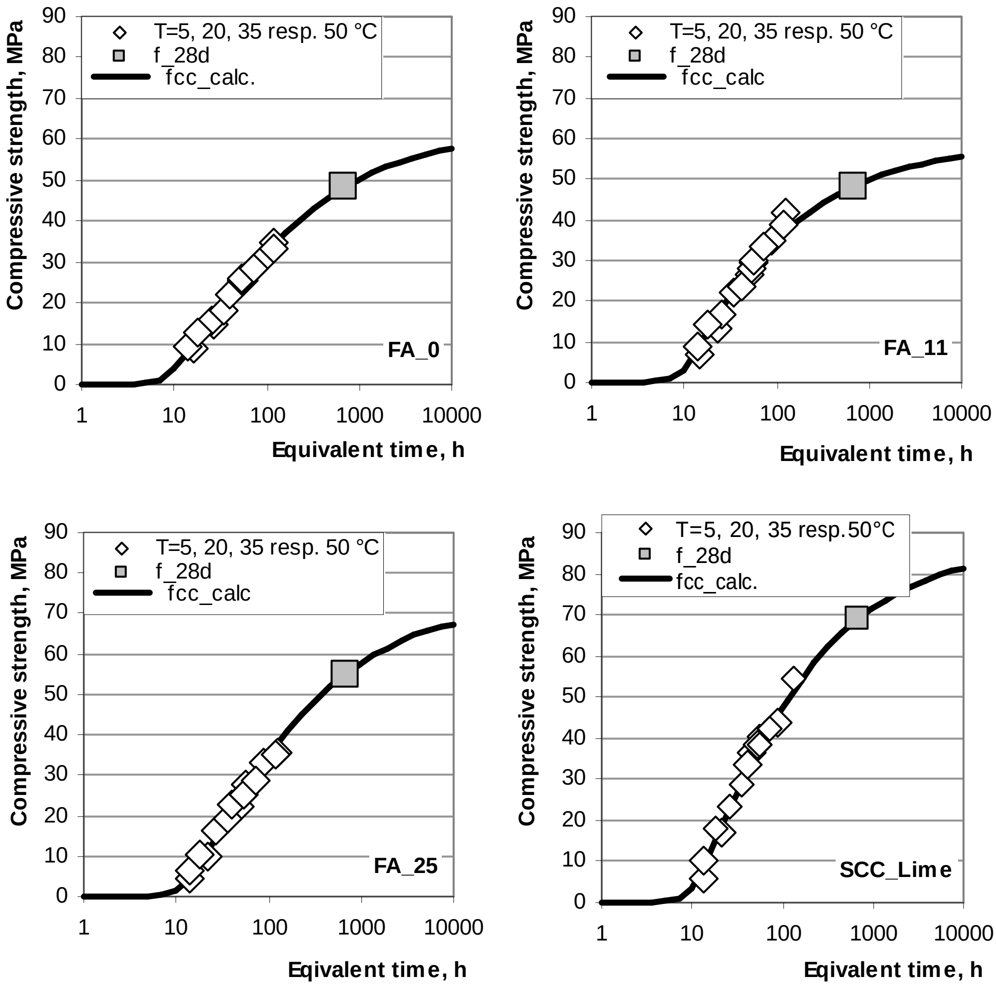

Figure 4 Evaluated strength growth for the tested mixes.

3.3 Creep tests

Measured creep values compared with individually evaluated creep functions are illustrated in Figure 5.The concrete mixes containing fly ash (FA_11 and FA_25) show significantly higher deformation at an early age loading (about one day after casting), in comparison with the concrete denoted FA_0 just containing Portland cement. At this early age of loading the mix SCC_Lime is somewhere in between. For loading at about seven days after casting all mixes show approximately the same deformation behaviour by time. Similar behaviour for concrete containing fly ash was reported by Ji (2008).

Parameters for the calculated curves shown in Figure 4 are presented in Table 3.

In the stress analysis, creep is considered by a numerical relaxation spectra calculated according to Jonasson (1977) and Jonasson and Westman (2001). Unfortunately, the number of values to numerically present the relaxation spectra is rather large, and those interesting in this specific data, please contact the writers.

Table 3 Evaluated individual parameters for the total deformation curves shown in Figure 4.

Parameter	FA_0	FA_11	FA_25	SCC_Lime
E_{28} [GPa]	28.5	27.1	29.8	36.2
s_E [-]	0.091	0.203	0.195	0.248
t_{SE} [d]	0.167	0.25	0.25	0.25
Loading at $t_0 \approx$ 1d:				
t_0 [d]	1.00	0.96	0.97	0.91
Δ_{t0} [d]	0.001	0.001	0.001	0.001
a_1 [10^{-12}/(Pa log-unit)]	1.5	13	8	7
Δ_{t1} [d]	0.1	0.1	0.1	0.1
a_2 [10^{-12}/(Pa log-unit)]	10	16	14	12
Loading at $t_0 \approx$ 3d:				
t_0 [d]	2.90	2.80	2.91	2.91
Δ_{t0} [d]	0.001	0.001	0.001	0.001
a_1 [10^{-12}/(Pa log-unit)]	1.2	2	2.5	3
Δ_{t1} [d]	0.1	0.1	0.1	0.1
a_2 [10^{-12}/(Pa log-unit)]	8.5	10	13	9.5
Loading at $t_0 \approx$ 7d:				
t_0 [d]	6.87	6.37	6.56	6.37
Δ_{t0} [d]	0.001	0.001	0.001	0.001
a_1 [10^{-12}/(Pa log-unit)]	1	2	1.5	1.2
Δ_{t1} [d]	0.1	0.1	0.1	0.1
a_2 [10^{-12}/(Pa log-unit)]	8	10	9	8.2

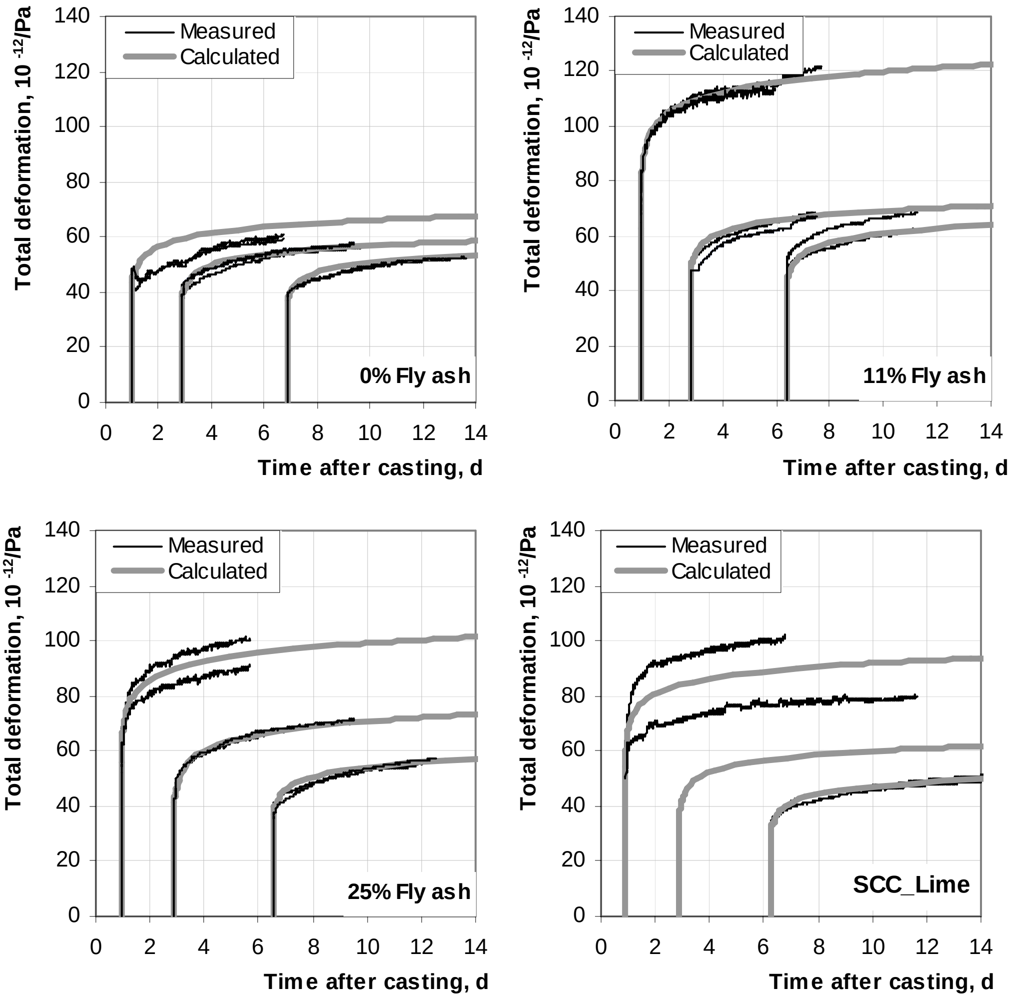

Figure 5 Measured creep compliance for the tested mixes and each individual evaluation.

3.4 Free deformation at variable temperature

The free deformation tests are performed on sealed cured specimens. Normally, the test can start approximately six to eight hours after casting, which is determined as the time when the formwork can be removed and the specimens are able to be handled and the deformation equipment can be mounted. The incorporation of fly ash delayed the hardening process and the measurements could not start within eight hours after casting. For the presented tests with fly ash concretes, the measurements started approximately 24 hours after casting, which precludes a direct comparison between the mixes with and without fly ash concerning the measured free deformation. The best-fit procedure behind Figure 5 is based on the following assumptions: regard the thermal dilation coefficient as constant for all three mixes FA_0, FA_11 and FA_25, and introduce adjustments only for the autogenous deformation. As can be seen in the figure, the measured deformation can be reflected by this technique.

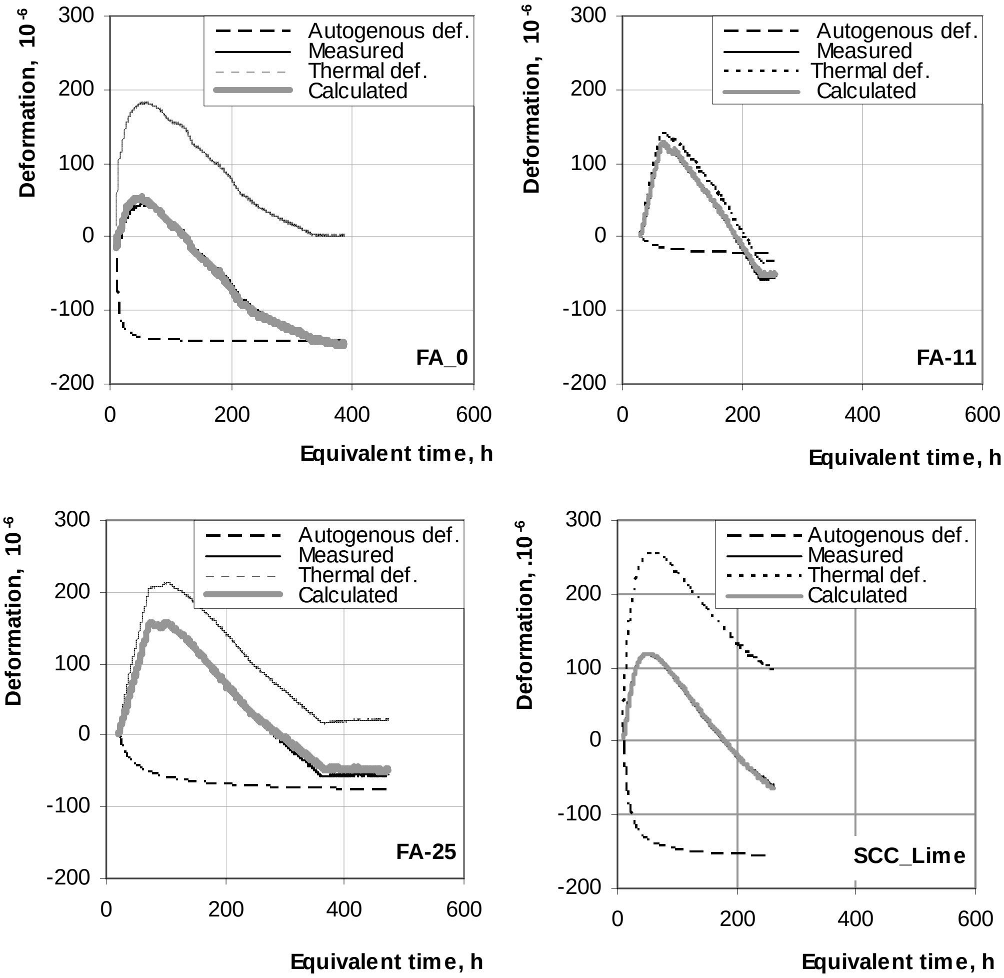

Figure 6 **Measured free deformation and the separated thermal dilation and auotogenous deformation.**

3.5 Stress growth at totally restraint conditions

None of the tested mixes cracked themselves in the TSTM. This can be seen either by the filled circles (= tensile strength when pulling the test specimens to failure in tension) that are bigger than the measured stresses at the same time, or by the dotted lines showing that the calculated tensile stress to strength ratios are lower than unity during the test period for all mixes tested, see further section 4.4.1.

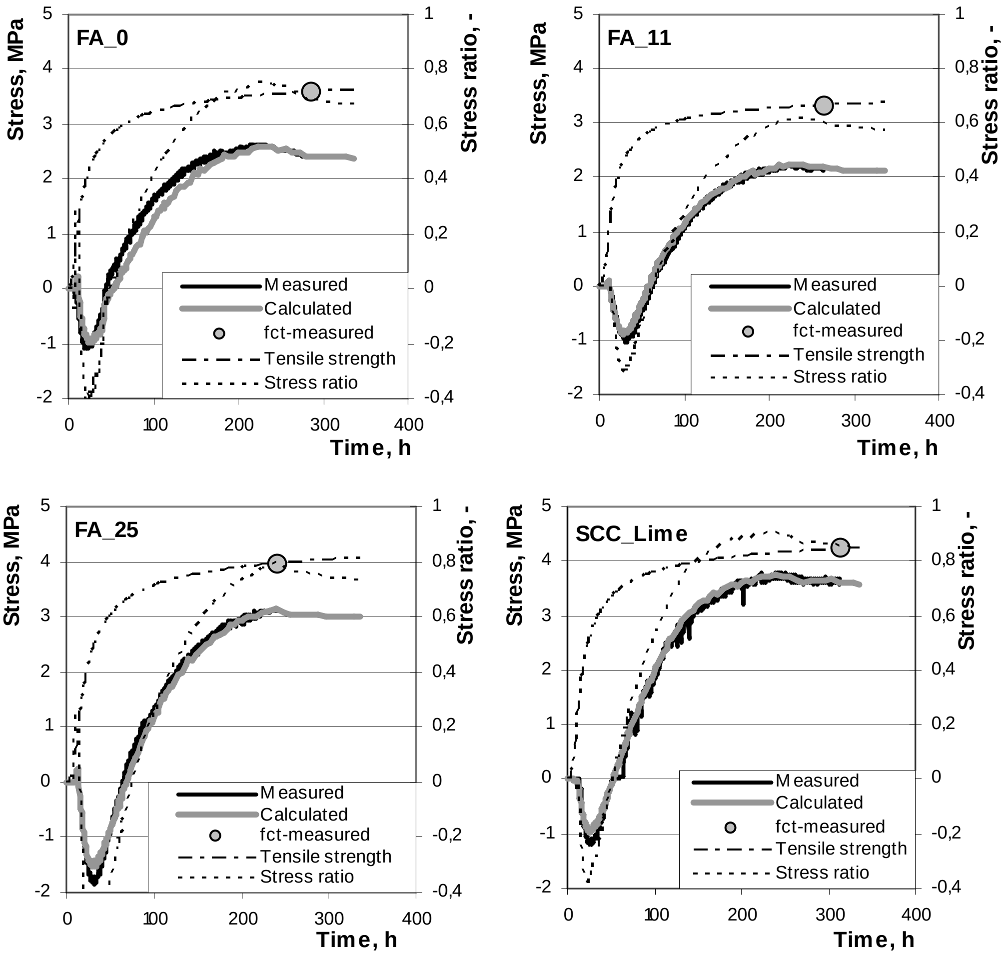

Figure 7 **Calculated and measured stress development at totally restraint conditions in the TSTM test.**

4 NUMERICAL STRESS ANALYSIS AND ESTIMATED CRACK RISK

4.1 Introduction

For some typical situations, which are examples within typical cases II, III and IV in Emborg et al (1997), temperature and stress analysis have been performed using the computer program ConTeSt (2008). The aim is primarily to compare estimated crack risks for the same structure applying data from the four evaluated mixes presented in this paper.

4.2 Types of cracks in young concrete

Generally, two main types of cracks may be distinguished (Bernander, 1998) as; cracks during expansion phase and cracks during contraction phase, see Figure 7. When analyzing self-balancing walls or slabs the terminology surface cracks can also be used as a characteristic identification of the expansion phase. For a typical situation when casting a wall on an existing slab, the terminology through cracks can be used as a characteristic identification of the contraction phase. The subsequent text in this paper is related to three chosen typical situations, for which the denotations surface cracks and through cracks are relevant.

Surface cracks: Surface cracks occur during the heating phase when the differences in temperature within the studied section cause tensile stresses that exceed the tensile strength. It can be prevented by lowering the temperature gradient within the cross section with different kind of measures (Bernander, 1998).

Trough cracks: Trough cracks occur when the contraction during the cooling phase is so large that the restraint from the adjacent structure causes too high tensile stresses in the newly cast concrete. Most common methods to avoid through cracking is cooling of the newly cast concrete or heating of the adjoining structure before casting the new concrete (Bernander, 1998 and Wallin et al, 1997).

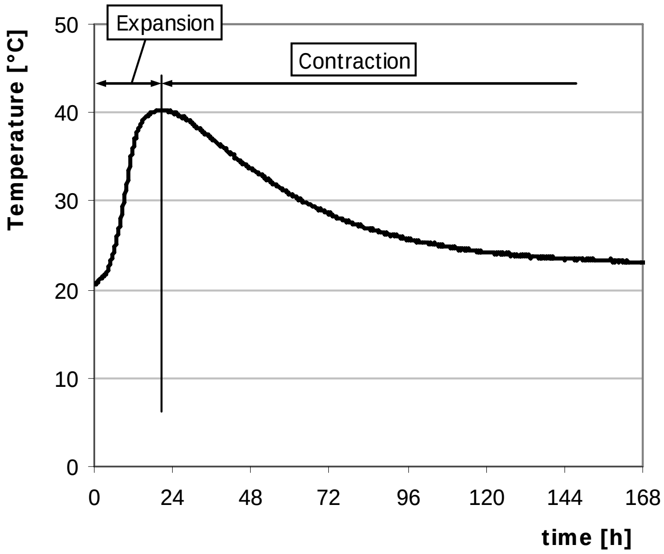

Figure 8 A typical temperature development for a hardening concrete structure. For the chosen typical situations the risk for surface cracks occurs during the expansion phase and the risk for through cracks occurs during the contraction phase.

4.3 Structures and boundary conditions

The risk for through cracking has been calculated on an assumed civil engineering structure illustrated in Figure 9. In the structure, the decisive point for through cracks is located in the lower part of the wall, approximately 0.5m above the casting joint between the slab and the wall. This is an example of typical case II in Emborg et al (1997).

The risk for surface cracks has been evaluated for two situations, one wall and one slab, which in Emborg et al (1997) are examples of typical case III and IV, see Figure 10.

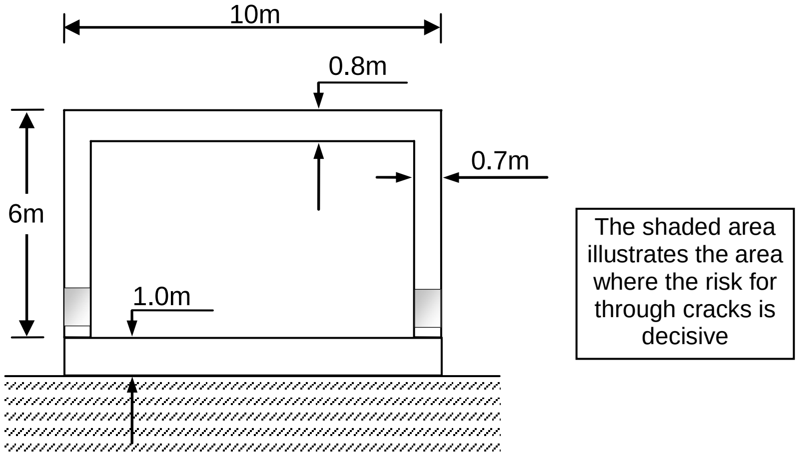

Figure 9 **Assumed civil engineering structure for calculation of risk for through cracking in the lower part of the wall. One example within the typical case II defined in Emborg et al (1997).**

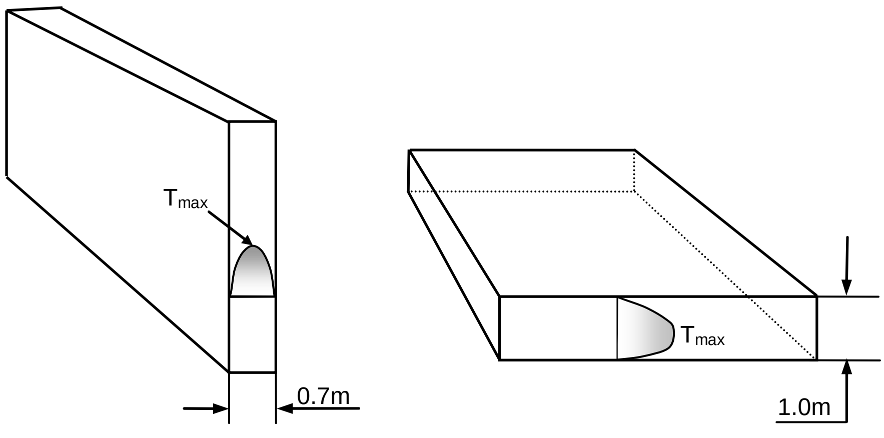

Figure 10 **Estimation of the risk for surface cracking has been performed for a) a symmetric wall (=example of typical case III) and b) for a slab on ground (=example of typical case IV). The typical cases are defined in Emborg et al (1997).**

The calculations have been performed at two different outdoor temperatures, 5°C and 15°C, respectively. The 22mm wooden formwork was removed after 7days. The wind velocity in the surrounding air is assumed to be 5m/s.

4.4 Results from the numerical analysis and discussion

According to the stress analysis, the highest tensile stresses in the walls, which may cause through cracks, occur approximately 0.5m from the bottom slab, see the shaded area in Figure 9. The calculated stress to strength ratio for all cases is presented in Table 4. For the self-balancing cases (III and IV) the calculated maximum temperatures are presented in Table 5.

Table 4 Calculated stress/strength ratios for the calculated mixes.

Climate	Mix	Stress ratio at risk of through cracking	Stress ratio at risk of surface cracking	
		Case II	Case III	Case IV
15°C	FA_0	0.59	0.31	0.67
	FA_11	0.50	0.18	0.41
	FA_25	0.55	0.28	0.73
	SCC_Lime	0.71	0.20	0.39
5°C	FA_0	0.82	0.35	0.71
	FA_11	0.60	0.18	0.42
	FA_25	0.68	0.27	0.94
	SCC_Lime	0.87	0.21	0.31

Table 5 Calculated maximum temperature in the wall section (Case III) and in the slab (Case IV).

Climate	Mix	T_{max} wall, °C	T_{max} slab, °C
15°C	FA_0	40.4	41.0
	FA_11	43.6	44.3
	FA_25	46.6	47.4
	SCC_Lime	43.4	44.1
5°C	FA_0	35.9	36.3
	FA_11	38.2	38.6
	FA_25	40.9	41.3
	SCC_Lime	38.3	38.3

4.4.1. Estimated risk for through cracks

The following conclusions can be drawn from the presented results in Table 5:

Case II: The concrete mixes containing fly ash show significantly lower risk for through cracks in comparison with the other two tested mixes, which is valid at both the analyzed outdoor temperatures. The mix with 11% fly ash content shows the lowest risk. The SCC mix containing limestone filler showed an increased risk for through cracks in comparison with the Portland cement concrete. In an earlier investigation presented in Utsi and Jonasson (2007), it was concluded that using SCC mixes containing limestone filler were as good as, or better, than ordinary Portland cement concrete with similar w/C-ratio. These conclusions were based purely on results from the TSTM.

Riding et al. (2008) have compared the effect of different types of fly ash on the early age cracking based on results from a TSTM. Four mixes with different fly ashes were tested at a 20% replacement of cement and these were compared to a reference mix without fly ash. The authors conclude that all mixes containing fly ash lowered the early age cracking risk even though the mixes containing fly ash had a lower tensile strength development than the control mix. The authors suspect that the lowered early crack risk mainly is an effect of reduced tensile strain in the material caused by a combined effect of lowered generated heat and increased early-age creep.

A direct comparison of the results from the TSTM for the tested mixes in this investigation does not show a significant improvement of the crack risk when fly ash is included, but a significant reduction using fly ash became obvious from the calculations on a real structure, especially at the lower outdoor temperature (5 ºC). The latter case might be an effect of better “natural” cooling by the surrounding air, as the generated heat is somewhat delayed compared with the use of solely Portland cement.

Ji (2008) has also shown a positive effect on the risk of through cracking when adding fly ash to concrete. Calculations were performed with computer program DIANA based on material properties tested in the laboratory. It was concluded that the mixes containing fly ash, 40% and 60% content of fly ash related to the cement content, significantly lowered the risk for through cracks. In these concretes the fly ash was partly replacing the cement.

Lee et al. (2003) have tested the autogenous deformation for high performance concrete (HPC) with and without fly ash. The early age stresses induced by restrained autogenous shrinkage were calculated using DIANA with general available creep functions. The authors concluded that adding fly ash significantly reduced the autogenous deformation for HPC in comparison with HPC mixed solely with cement. From the numerical analysis it was concluded that the induced stresses were lowered by the use of fly ash, but with lack of data on tensile strength and creep they can not conclude whether the crack risk are lowered or not.

The results presented in this paper indicate that fly ash in concrete lowers the risk for through cracking for the typical situation shown in Figure 9. It shall be pointed out that fly ash has been added as a replacement of part of the aggregate, which causes an increased heat development in comparison with the reference mix. In case of fly ash added to concrete by a partial replacement of cement, the crack risk will probably be further decreased.

4.4.2. Estimated risk for surface cracks

Based on the results, the following conclusions regarding surface cracks in the wall and the slab can be drawn:

Case III: The calculated surface crack risk in the wall section is very similar independent from the surrounding temperature and concrete composition. All mixes show low risk for surface cracks, which is in accordance to results presented in Emborg et al. (1997). The mix containing 11% fly ash has the lowest stress to strength ratio, which might be an effect of the early creep behavior in combination with the moderate temperature development.

Case IV: The mix containing 25% fly ash shows the highest risk for surface cracks in the slab. In lower temperatures, the stress to strength ratio is nearly unity (0.94), which reflects a very high crack risk. In addition, the mix containing 11% fly ash does not show the lowest crack risk as in case II and case III. The risk for surface cracks is a combined effect from the heat development and the early-age creep. The increased crack risk for the 25% fly ash mix is probably an effect of the increased temperature; see Table 3, which is a combined effect of increased binder content and the temperature balance situation for a 1m thick slab on ground. The positive effect from an increased early-age creep has probably been compensated by the increased temperature. If the mixes have been composed adding fly ash as partial replacement of the cement, the heat evolution decreases. This would lower the temperature development, but the effects on surface crack risk have to be evaluated individually for each mix.

SCC_Lime reaches the lowest stress to strength ratio regarding surface crack risk in the slab. This mix has, similar to the fly ash concretes, shown an increased early-age creep in comparison with the Portland cement concrete. In addition, SCC_Lime does not reach as high temperatures as the 25% fly ash mix. The increased early-age creep together with a lowered temperature development are probably the main factors behind the decreased stress ratio.

5 SUMMARY AND CONCLUSIONS

- Established numerical models describing the properties of hardening concrete can be applied on concrete containing fly ash.
- The mixes containing fly ash and limestone filler had an increased early-age creep.
- The mixes containing fly ash had a higher heat development caused by increased binder content, as fly ash was added as replacement of part of the aggregate. However, a numerical stress analysis, for a typical situation in civil engineering construction, has shown that the risk for early age through cracks is significantly de-

creased for the mixes containing fly ash. In case of adding fly ash to concrete by a partial replacement of the cement, the crack risk will probably be further decreased. The positive effect from fly ash regarding the risk for through cracks could not be evaluated solely from the TSTM results.

- The risk for surface cracks in the analyzed wall (0.7m) is very small for all of the evaluated mixes in both of the tested temperatures. Other dimensions have to be studied separately.
- The estimated risk for surface cracks in the analyzed slab (1m) on ground was not improved by an incorporation of fly ash. The mix containing 25% fly ash had the highest risk for surface cracks in the slab. It is probably an effect from the increased heat development in combination with the thickness of the slab. The increased heat development has probably compensated the positive effect from the increased early-age creep for concrete containing fly ash.
- The estimated risk for surface cracks in the slab for concrete containing limestone filler was significantly lower. It is probably a combined effect from moderate heat development and increased early-age creep.

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