Form Pressure Generated by Self-Compacting Concrete — Influence of Thixotropy and Structural Behaviour at Rest

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Preface

The research project presented in this thesis was carried out at the Swedish Cement and Concrete Research Institute in Stockholm (CBI) and the Royal Institute of Technology (KTH), School of Architecture and the Built Environment, Division of Concrete Structures in Sweden between August 2002 and September 2006. It deals with the reversible thixotropical and irreversible structural behaviour of Self-Compacting Concrete (SCC) at rest and the influence these characteristic properties has on the form pressure. The focus has been set on the development of methodologies suitable for measuring these characteristics and investigations on the parameters influencing them.

This project was initiated as a direct follow up of a previously conducted research project, “Self-Compacting Concrete – Technique of Application”, which was carried out in close cooperation between the Swedish Road Administration (SRA) and CBI (see Paper 3). In this context I want to thank Matti Huuskonen, SRA, who at an initial stage supported the idea to form this project.

I want to direct my gratitude to the academic supervisors of this project; Professor Johan Silfwerbrand (KTH/CBI) and Professor Jonas Holmgren (KTH), for their support and trust in me. The reference group of this project consisting of Hans Bohman, SRA, Anders Huvstig, SRA, Thomas Österberg, SRA, Mats Emborg, Betongindustri, Hans-Erik Gram, Cementa, Åke Skarendahl, BIC, Bengt Ström, NCC, Lutfi Ay, Skanska, and the supervisors, has contributed with valuable advices and discussions.

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My CBI colleagues are all to be appreciated for everyday support, their contribution to a nice office atmosphere and superb corridor discussions. A special thanks to Tuula Ojala, the librarian at CBI, who never fails in finding any possible information.

Thanks to my mother and family for all the support you have given me and most especially I want to thank my sister, Kristina, who helped me through some tough times – indeed a priceless help.

Finally, I want to send all my love to the apples of my eye, my daughters Johanna, Paulina and Josefin, for making everything worth while.

Stockholm, September 2006

Peter Billberg
Summary

Self-compacting concrete (SCC) offers a rational and fast casting process since this fluid concrete merely has to be poured, or pumped, into the formwork without any compaction work needed. But this can be at the cost of high form pressure. However, reported results show that SCC can act significantly thixotropic, i.e., build up a three dimensional structure at rest, and this can reduce the form pressure considerably. Thus, in order to utilise the favourable possibilities to increase effectiveness without risking form collapses, the need arises for a deeper and broader understanding of the mechanisms behind this thixotropic behaviour. This is the aim and focus of this present doctoral project.

Methodologies have been developed for the characterisation and measurement of the structural build-up at rest, both for the fluid phase (the micro mortar phase) and the concrete itself. Here the hypotheses state that the thixotropic mechanisms originate within the colloidal domain and thus, support the studies of the fluid phase where this domain is found. The methodologies are based on the hypothesis stating that the magnitude of the structure can be represented by the maximum elastic stress the fresh material can withstand before the structure breaks. Thus, stress-strain measurements are preformed where the transformation of the material from elastic to plastic and further on to viscous can be recorded. This is done at various times at rest.

The results show that both micro mortar and SCC are thixotropic and this behaviour is influenced by every measure taken influencing the forces acting on the colloidal particles. Examples of such measures are: particle concentration and fineness (influencing the inter particle distances), dispersing agents and the dispersing mechanism (molecules working at the solid-liquid interface), viscosity modifying agents (attract water and form structures through molecule entanglement), and clay minerals (forming card-like structures).

The time-dependent structural build-up of SCC is a function of an irreversible structure (slump-loss) and the reversible, true thixotropic structure. The methodology developed enables to quantify these parameters separately. The latter (irreversible) one can dominate in some cases and this project reveals how sensitive the SCC can be to small variations of the constituent materials. This is in fact one of the more important topics recommended for further research.

There is apparently a threshold value of the structural build-up necessary to reach before any significant reduction of form pressure is obtained. Housing SCC’s, with a W/C ratio of 0.58, show low degree of structural build-up and pressure decrease while civil engineering SCC’s can show the opposite, but this at the cost of severe slump-loss.

Recommendations are presented and for the nearest future, they suggest a conservative standpoint regarding design of formwork systems when SCC is used. This project has merely focused on material properties and thus, not incorporated the number of well known parameters also influencing the form pressure and linked to the formwork, reinforcement temperature etc. Further research is needed and the mapping of influencing parameters in order to create a design model must continue in future before a safe predicting of the form pressure can be done. If the behaviour of a SCC is known it should be used to optimise the formwork. If not, calculating with hydrostatic pressure should be done or the knowledge missing should be gained by using this methodology. A third option is given and this is to monitor the form pressure in real time using sensors.
Sammanfattning

Inledning

Denna doktorsavhandling handlar om studier av självkompakterande betongs (SKB) tixotropa och strukturella beteende i vila och hur detta beteende påverkar formtrycket. Arbetet har genomförts på Cement och Betong Institutet (CBI) och inom ämnet Betongbyggnad på Kungliga Tekniska Högskolan mellan augusti 2002 och september 2006. Projektet är en direkt följd av ett tidigare samarbetsprojekt mellan Vägverket och CBI, ”Självkompakterande betong – användningsteknik” (se artikel 3) och har finansierats av Vägverket, NCC, SBUF samt konsortiet för finansiering av grundforskning inom betongområdet.

Bakgrund

Självkompakterande betong (SKB) började utvecklas av Tokyo University i mitten av 1980-talet och forskning inom denna teknik initierades i Sverige av CBI i början av 90-talet. Denna forskning ledde senare fram till två parallella projekt; (1) ett samarbetsprojekt mellan CBI och Vägverket i syfte att ta fram självkompakterande brobetong enligt Bro 94 och (2) det första Brite EURam projektet om SKB (koordinerat av Marianne Grauers, NCC). Det förstnämnda projektet ledde fram till att tre fullskaliga plattrambroar göts med SKB under vintern/våren 1998.


Som en direkt följd av dessa upptäckter initierades det tidigare nämnda projektet ”Självkompakterande betong – användningsteknik” som syftade till att studera just formtrycket vid gjutningar med SKB. Bland annat resulterade en rad av fullskalegjutningar i att ett starkt samband mellan gjuthastighet och formtryck erhölls. Under detta projekt identifierades behovet att fördjupa studierna av mekanismerna bakom denna tixotropa strukturuppbyggnad och därför initierades detta doktorandprojekt.

Litteraturstudie

En omfattande litteraturstudie har genomförts och den har fokuserat på en rad olika områden. Inledningsvis ges en historisk bakgrund till detta vetenskapsfält och vidare grundläggande karakteristika för tixotropa material, kolloidal- och ytkemi som förklarar de interpartikulära krafter som påverkar partiklar i suspension, mätmetoder för studier av tixotropi samt metoder för att styra tixotropi. Dessutom redogörs för studier av cementbundna materials tixotropi, från pasta till konventionell betong och till SKB, för specifika studier av SKB och formtryck samt slutligen för rapporterade försök att skapa modeller för att beräkna formtrycket vid gjutning med SKB. Litteraturstudien visar bland annat att cementbundna material är tixotropa.
till sin natur och att strukturuppbrytningen vid störning är signifikant men sker med lägre hastighet än strukturnedbrytningen vid störning.

Hypoteser

Fyra hypoteser som bland annat ligger till grund för val av metodik ställs upp:

– De grundläggande mekanismerna bakom cementbundna materials strikt tixotropa egenskaper återfinns i de koloidala interaktionerna mellan partiklar i betongens vätskefas, pasta- eller mikrobruksfasen, och i detta sammanhang bedöms de större ballastpartiklarna helt inerta.

– Den totala strukturuppbrytningen hos SKB i vila är en funktion av ett reversibelt, strikt tixotrop, beteende och en irreversibel förändring över tid, dvs. en konsistensförlust.

– Strukturen representeras av den färska betongens elastiska egenskaper och den maximala spännings som strukturen kan motstå innan den bryts karakteriseras dess storlek.

– SKB är ett material som bygger upp en struktur i vila och denna egenskap påverkar formtrycket.

Mikrobruksfasens tixotropi och strukturuppbrytning i vila

Metodiken för studier av mikrobruksfasens strukturuppbrytning utnyttjar den använda reometerens (Physica MCR300) möjlighet att styra spänningen och registrera responsen i form av deformation. Mätsekvensen inleds med mätning av konventionell rotationssyrdf reologi varefter reometer styr om till att med tio minuters mellanrum i vila öka spänningen tills strukturen bryts. Detta kontrolleras genom kriteriet att skjuvfastigheten (deformationsresponsen) inte får överstiga 0,2 s⁻¹. Efter en sammanlagd vila på ca 40 minuter slås återigen instrumentet till att mäta konventionell reologi (efter att mikrobruket blandats i tre minuter för att bryta ned den reversibla strukturen). Således kan den reversibla strukturen separeras från den totala och den reversibla erhållas. Denna utgör arean mellan dessa tidsmässiga strukturutvecklingar (totala respektive irreversibla).

Resultaten är rapporterade i artikel 1 och slutsatserna som redovisas stöder hypotesen att samtliga åtgärder som påverkar kraftspelet mellan partiklarna resulterar i förändringar i tixotrop respons. Bland dessa åtgärder som ökar tixotropin nämns: minskad flytmedelsdos, flytmedel med elektrostatisk dispergeringsmekanism jämfört med sterisk dito, ökad partikelkonzentration och finhet hos fillermaterial, tillsats av luftporsbildare samt tillsats av viskositetsmedel och lermineral.

Betongens tixotropi och strukturuppbrytning i vila

Denna etapp inom projektet inleddes med omfattande försök att skapa bro-SKB med samtidigt väsentligt öppethållande och stabil lufthalt. En rad olika parametrar befanns påverka öppethållandet, en del mer logiska medan kunskap saknas för att förklara andra. Slutligen kunde dock målet uppfyllas genom lämpligt val av flytmedel, luftporsbildare, finballast och blandningsordning och etappen genomföras.

Metodiken är uppbyggd på samma sätt som för mikrobruken men styrningen av betongviskometern (ConTec 4) fick provas fram då den inte förmår styra spänningen utan endast deformationen (rotation av yttercylindern). Den yttre cylindern befanns kunna styras
till mycket små rotationshastigheter (motsvarande ett varv på över 22 minuter) som manuellt kunde initieras vid olika tidpunkter under viloperioden. Därmed kunde metodiken baseras på spännings-töjningsmätningar och således kunde den karakteristiska elastiska egenskapen kvantifieras.


Metodik och resultat är rapporterade i artikel 2 och 4 och slutsatserna är att SKB bygger upp struktur i vila och att denna består av en reversibel och en irreversibel komponent samt att metodiken förmår skilja dessa åt. SKB beter sig töjnings-hårdnande då vilan sker under inverkan av en skjuvsplånning. Strukturuppbryggnaden är i princip helt linjär med tiden och detta ger möjlighet att förutse strukturuppbryggnaden över tid genom mätningar under endast en kort tid av vila. Även här visas att partikelkonsentration, partikelfinhet, flytmedeldos och –typ påverkar strukturuppbryggnaden.

**Simultan mätning av strukturuppbryggnad och formtryck**

Ett rostfritt rör har tillverkats och försetts med fem tryckceller på olika höjd över botten. Övertrycket (luft) i röret kan regleras för att simulera högre gjuthöjder och för att simulera olika gjuthastigheter. Det visas att tryckcellerna är tillförlitliga och likaså metodiken i stort. En begränsning som beror av övertryckets inverkan på rördiameter samt betongens långt gångna tillstypvänd diskuteras. Men den praktiska begränsningen för metodiken avfärdas. Likaså diskuteras inverkan av övertrycket på resonemang kring passiv eller aktivt tryck och leder till att övertrycket inte tycks inverka på formtrycksreduktionen utan detta beror på betongens strukturella förändring under vilan.

Rekommendationer

Kartläggnningen av materialegenskaperna för SKB har inletts i detta projekt och verktyg för kartläggnningen är framtagna. Men ytterligare forskning behövs för studier av fler delmaterial och kemiska tillsatsmedel. Därför bör man i den närmsta framtiden inta en konservativ hållning inför frågan om dimensionering av formar där SKB skall användas. Detta innebär att om kunskap finns om hur en SKB biter sig skall denna naturligtvis användas för att optimera formen. Men om ett nytt koncept (ny gjutteknik, recept eller temperatur etc.) skall användas bör antingen hydrostatistisk tryck förutsättas eller så bör detta koncept provas med den metodik som tagits fram i detta projekt. Ett ytterligare alternativ är att förse formarna med sensorer och därmed följa tryckutvecklingen i realtid.

Hus-SKB med vct 0,58 som ingått i detta projekt visar på låg grad av strukturuppbyggnad och liten sänkning av formtryck inom relevant tid. Vid normala våningshöga gjutningar ter det sig därför mer ekonomiskt att konstruera formarna för hydrostatistiskt tryck och medge en hög gjuthastighet. Vissa bro-SKB visar en mycket gynnsam formtryckssänkning på kort tid, men detta på bekostnad av öppenhållandet. Vid gjutning med bro-SKB som har långt öppenhållande bör försiktighet iakttagas eller specifik kunskap inhämtas.

Det är viktigt att komma ihåg att detta projekt genomförts i sin helhet i laboratoriemiljö. Studierna har koncentrerats på materialparametrar för självkompakterande betonger, med för svenska betongbranschen relevanta recept, och mindre på formsystem och miljöparametrar. Således är det många parametrar som i praktiken påverkar formtrycket som ligger utanför detta projekts omfattning. Metodiken och kunskapen från detta projekt måste således inkorporeras i en större och mer övergripande modell för beräkning av formtrycket vid gjutning med SKB.

Till sist kan det inte tryckas hårt nog på att i den situation som idag råder, dvs. situationen med de kraftiga variationerna i färska egenskaperna hos SKB beroende på stor känslighet, kan inte en säker bedömning göras av hur formtrycket kommer att utvecklas vid gjutning med SKB med flera olika levererade lass. För SKB som koncept i stort är forskning kring variationsstabil SKB ett måste.

Fortsatt forskning


Fältstudierna föreslås omfatta de parametrar som laboratoriestudier svåriligen kan hantera. Bland dessa föreslås avseende formen att studera inverkan av geometrin, olika ytor (ytmaterial), formens permeabilitet, släppmedel och formens styrheter. Även armeringens inverkan bör studeras. Det har i vissa fall rapporterats att strukturen som byggs upp i SKB i vila kan vara svag nog att signifikant störas av exempelvis vibrerande maskiner eller fordon på arbetsplatsen och detta bör kartläggas.
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Appended Papers (Nos. 1 – 5)
Chapter 0

Content of the thesis

The following five papers are included in the thesis and comprise the experimental work performed in the project:


Peter Billberg’s contribution to the papers with co-authors, i.e, Paper No. 3 and 5:

Peter Billberg has drawn up the proposals for the methodology, independently performed the trials, worked out the analysis and conclusions and written the papers. The co-authors have contributed with the choice of subject and their view on methodology, analysis, conclusions and text.
Chapter 1

Introduction

1.1 Background to the present project
The development of self-compacting concrete started in Japan (Tokyo University) in the mid 80-ies with the aim to reduce durability problems in complicated and heavily reinforced concrete structures due to lack of skilled workers and a poor communication between designers and construction engineers, Ozawa et al. (1992). Even though conventional concrete previously (and still today) in some applications was cast without any compaction, this new concrete was deliberately designed to be able to fill every corner of the form and encapsulate all reinforcement with maintained stability only under the influence of gravitational forces. However, this applied research would not have been possible without the application of nanotechnology in the research and development of surface active molecules used in chemical admixtures, Skarendahl and Billberg (2006). Examples of such admixtures are the third generation of superplasticizers and viscosity modifying agents enabling a controllable rheology, i.e., SCC fluidity and segregation resistance.

This technique was adopted by the Swedish Cement and Concrete Research Institute, CBI, in the early nineties and the development started in Sweden as one of the first countries outside Japan. Beginning in 1997, as a following of a promising initial project, the first Brite EuRam project on SCC financed by the European Union, was coordinated by Marianne Grauers at the Swedish contractor NCC, Brite EuRam (2000). Another project dealing with development and adoption of civil engineering bridge-SCC to the national Bridge Code was running parallel to this, Billberg et al. (1999). This latter project was performed in co-operation between CBI and SRA (Swedish Road Administration) and was finalised with the constructing of three bridges during spring 1998, i.e. the first structures outside Japan cast entirely with SCC.

Before these full-scale castings of bridges during the spring of 1998, it was assumed that the form pressure should be high or even equal, or close to, hydrostatic. This assumption was reasonable since all pre-qualifying tests performed in advance of the castings had shown that the tested SCC mixes kept their very fluid consistency for at least 60 minutes after mixing. And since casting was planned to be executed well within 60 minutes from mixing it was believed that the concrete would behave as a liquid also in the form. However, measurements of the lateral form pressure were made during the first bridge casting in January 1998 and quite opposite to what was presupposed, the pressure was far from hydrostatic, Ikäheimonen (1998). In fact the pressure was even lower than the design values for conventionally vibrated concrete, see Fig 1.1.
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The maximum measured pressure was 18 kPa which should be compared to the value representing hydrostatic pressure, i.e., 127 kPa for the 5.4 m high wall. Thus, the pressure reached only 14% of the hydrostatic pressure. The casting rate used was 0.9 m/h.

The only relevant conclusion of this rather surprising result was that the SCC used had a pronounced thixotropic property. That is, keeping its flowing properties as long as it was kept in motion but once left at rest in the form, it starts to build up a structure able to withstand pressure from concrete above without increasing the horizontal pressure against the form.

In the mid and late nineties, the development of SCC started worldwide and the first international RILEM symposium was held in Stockholm 1999 and since then a symposium has been held every second year; Tokyo 2001, Reykjavik 2003 and Chicago 2005. In September 2007 the next symposium will be held in Ghent. An indication of how the interest has increased regarding form pressure when using SCC is shown in Fig 1.2 representing the number of papers at the RILEM symposia mentioning “form pressure” in the heading. Also the number of papers discussing thixotropy is presented in Fig 1.2.
The finding in the pilot project, Billberg et al. (1999), of the low form pressure deviated considerably from hydrostatic pressure resulted in a new Swedish project aiming to focus on the form pressure when SCC is used, Billberg and Österberg (2002) and Billberg et al. (2005) (Paper No. 3 in this thesis). Some of the results from this latter project are shown in Fig 1.3.

![Fig 1.3. Final pressures for the seven SCC mixes and a conventionally vibrated concrete (mix 8) in % of the hydrostatic pressure in relation to the casting rate (m/h). From Billberg and Österberg (2002) and Billberg et al. (2005).](image)

Note that mix 5 is excluded from the regression showed in Fig 1.3 because of difference in consistency and age (at casting) relative to the other mixes and also mix 8 since it is a conventionally vibrated concrete.

One of the major conclusions from this project was that the casting rate was found to correlate to the maximum pressure, indicating that the longer time at rest, the more the concrete could resist vertical load without increasing the lateral pressure. Thus, it was confirmed that the SCC mixes built up a time-dependant structure at rest.

The interest of the mechanisms behind this thixotropic behaviour now led to that this present project was started and formed as a doctoral project, see further the scope and aim in Chapter 2.

### 1.2 Factors influencing the pressure of concrete on formwork

There are a great number of factors influencing the form pressure generated by fresh concrete. In Gardner (1985) the following factors are listed: concrete density, vibration, revibration, form geometry, temperature, casting rate, concrete consistency, chemical and mineral admixtures and pumping concrete from the top or the base. In Clear and Harrison (1985) another list is reported which in some respects overlap the former but some additional factors are recognised: aggregate shape, form permeability or water tightness, roughness of the sheeting material, slope of the form, stiffness of the form, and impact from concrete discharge, in air or under water.

The following discussion relates to the factors listed in Gardner (1985) and Clear and Harrison (1985):

For conventional vibrated concrete the density influences the form pressure while the concrete is in a fluid state which is the case directly after casting and during vibration (or when concrete is revibrated). The increased concrete shear strength (shear strength inversely
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proportional to the fluidity of the concrete) is a time-dependent process and an increased casting rate decreases this time and thus, leads to higher pressures. The shear strength is also related to consistency and temperature and consequently, a higher slump value increases the pressure which also a lower temperature does due to the influence on the development of shear strength. The general discussion regarding admixtures relates to this influence on retardation, i.e., the influence on the time-dependence increase of shear strength. Any admixture increasing the retardation of shear strength development leads to higher pressure.

The aggregate shape relates to the friction between the particles influencing the shear resistance of the concrete. The influence of coarse aggregate on the pressure for SCC was investigated by Assaad (2004) and found to be significant. The increase of coarse to total aggregate ratio reduced the initial pressure as well as the decrease of pressure with time. The explanation reported by Assaad (2004) is that this is due to interlocking of aggregate particles causing an arching phenomenon. Also the maximum size was investigated and the influence was found to relate to packing in that a favourable packing generates lower pressure due to less mobility of the settled SCC at rest.

The form geometry is also important since the shear forces at the wall (due to friction between concrete and wall) become small relative to the concrete mass the bigger the form dimension is. Consequently, a denser reinforcement configuration increases these supporting frictions forces and lowers the lateral stresses against the wall. The permeability and roughness of the form material influences the friction between the form surface and the concrete. Permeability decreases the pore water pressure due to leakage of water through the form surface while the increased friction due to an increased roughness is obvious. If one side of the form is sloped (i.e., non-parallel form sides) it means that the plane area varies with the height and thus, vertical casting rate is not constant even though the cast volume per time unit is constant. Recalculation is thus needed. Generally a stiffer form results in higher pressures. The explanation is that a pressure reduction due to a yielding of the form allows the arching to occur, Rodin (1952). The height of discharge of the concrete (pouring height) influences the impact forces.

For the case where the concrete is pumped from the base of the formwork, the design value for the pressure should be the hydrostatic pressure plus the pump pressure. The reason is of course because the concrete is in motion during the whole casting procedure without any possibility for the concrete shear strength to develop.

Finally, casting under water enables to account for the buoyant weight density, i.e., density of concrete minus density of water.

For SCC the vibration is not an issue but the discussion of the time-dependant increase of shear strength, form geometry and surface and reinforcement is hypothetically still valid. And thus, also factors influencing this time-dependent behaviour (colloidal forces and surface active components), which is the basis for this present project (see also Chapter 2), are interesting.
1.3 The importance of correct judgements of design loads for formwork systems

According to ACI SP-4 (1989), the formwork costs are somewhere in the range between 35 and 60 % of the total cost for a normal concrete structure. For the Swedish market it is common to relate the formwork costs to approximately a third of the total cost of a concrete structure, Bohman (2006). Thus, the importance of correctly designing formwork for concrete must not be disregarded. If the design loads used are underestimated it can lead to problems of various degree of seriousness. And if overestimated it will make the cost of the formwork much higher than necessary. In case of the underestimated lateral pressure, in the best case the deflection of the formwork ruins the geometry of the structure proportional to the degree of how much the pressure deviates from the design value. In the worst case the formwork collapses with injuries or even fatal consequences. SCC enables the casting process to be increased far above the rate for which conventional vibrated concrete can be cast. In the latter case the concrete is cast in lifts of which each has to be vibrated and this process limits the rate. In practice, not taking the pressure into account, the limiting casting rate for SCC is probably only governed by the capacity of the deliverance to the site.

So, the importance of understanding how SCC influences the form pressure is a question of a balance act between increased production efficiency on one side and safety aspects and finished structural quality in terms of geometry on the other side.
Chapter 2

Aim and scope

2.1 General
The initial project aim was to deepen the understanding of how the thixotropic properties of self-compacting concrete influence the form pressure and the surface finish of the casting lift. However, the focus was early limited to the form pressure influence. The knowledge will contribute to a more efficient and environmentally friendly production, both regarding resources and working. By efficiency it is meant that concrete structures can be built at lower costs at the same time as the product itself gains higher quality and thus, reduces the need of repair due to casting failures. This will affect short term investments as well as long term maintenance costs and therefore results in an overall cost reduction for the whole society. In the long run also the outtake of nature resources will benefit from the self-compacting concrete technique due to, e.g., the possibility to use waste products as powders, less wear of form material enabling them to be reused and less energy needed due to an increased productivity.

It is today a well known fact that production of concrete structures is a hard and risky work, maybe most pronounced in production of civil engineering structures. It is far too common with noise and repetitive strain injuries for concrete workers and it is relatively rare that these workers retire at the normal 65 years of age (as in Sweden) but instead before this age. The technique of self-compacting concrete offers a better working environment in that the working site gets quieter which in terms leads to less noise damages, less disturbance of neighbours and not least a safer work site. The heavy compaction work is minimised making the work considerably less wearing and thus, it is favourable for the existing concrete workers as well as for the recruitment of new workers.

2.2 Specific aim
The hypotheses this project aims to verify and quantify are principally those stating that the particle concentration and choice of superplasticizer type and dose influence the thixotropy, i.e., the influence of interparticle distances in the colloidal domain (see Section 3.2) and the dispersing mechanisms of the superplasticizer molecules. The two different concepts; housing SCC and civil engineering SCC, will be studied, respectively.
2.3 Limitations
The number of parameters influencing the form pressure of concrete is large as discussed in the previous Chapter 1 and many of them are not included in this project. The parameters included are mainly the material properties (as described in the last Section) and the rate of casting. Thus, no variations of form geometry, form material, reinforcement arrangement, temperature, concrete density or deliberate difference in consistency (slump-flow) are investigated. In addition, the aim is to study SCC mixes that are relevant to be used in full-scale castings on the Swedish market and thus, no such additives as fly-ash, blast furnace slag or cements from outside Sweden are included. Even though sometimes used, silica fume is also left out from the test series.

The focus is set on methodology for the characterisation of structural time-dependent changes of SCC fluid phase, i.e., the micro mortar phase, and of SCC and for the measurement of form pressure in laboratory scale enabling simulations of castings with variable heights and rates.

2.4 Implementation
The results aim at enabling the planning and execution of more efficient, environmentally friendly and safe casting of concrete structures. In a further perspective they will also be used to form a foundation for a revision of the design rules of formwork regarding lateral pressure.
Chapter 3

Literature survey

3.1. Introduction

This initial Section is mostly taken from four general reviews regarding thixotropy, Barnes (1997), Cheng (1986), Mewis (1979) and Bauer and Collins (1967).

3.1.1 Historical background

The term thixotropy was first introduced by Peterfi (1927) (reported by Barnes (1997) and Mewis (1979)) to describe the isothermal and reversible transformation of a material from a gel to a liquid by mechanical disturbance and thus, the interest for thixotropy is almost as old as the modern science of rheology. The word thixotropy is put together by the two Greek words “thixis” (stirring, shaking) and “trepo” (turning, changing). The first time the concept of thixotropy was mentioned in the title of an article was in 1935 when Freundlich published the book “Thixotropie” where he described the flow characteristics of aluminate hydroxide gels, Freundlich (1935). Later on a number of other systems were found to show thixotropic properties. Examples of these are suspensions of vanadium pentoxide, starch pastes, gelatine gels, pectine gels.

Examples of early performed work in the field of thixotropy are the three articles of McMillen published in 1932 (reported by Barnes (1997)) where he describes his investigation of a large number of paints, McMillen (1932). In 1942, an English scientist, Scott-Blair, wrote a book “A Survey of General and Applied Rheology” (reported in Barnes (1997)) in which he refers to around 80 articles on thixotropy, Scott-Blair (1943). In the next edition of this book, published in 1949, approximately 120 articles are referred to and he lists articles describing instruments developed especially for measurement of materials thixotropic properties. He raised the question, which is still today a controversial question, if thixotropy shall be measured at a constant stress or at a constant deformation rate. He also sites Hamakers explanation of thixotropy as dependant of the "secondary attraction minima" (see Section 3.2.2) so that the particles can build a weak structure which easily can be broken down but also be built up again at rest. This explanation is still today valid, Barnes (1997).

The difference between thixotropical and shear thinning behaviour is only that of the time for the structure to re-group during shear or at rest. When a material is shear thinning it changes the microstructure instantly while a thixotropic material is time dependant. But with today’s knowledge of microstructural changes it is probably safe to say that shear thinning materials
also are thixotropic since it always takes time, even though limited, to create the re-grouping of the microstructural elements to result in shear thinning.

Thixotropy is one of the few terms within the European rheology society’s that have survived from the pre-war period until today.

3.1.2 Definition of thixotropy

The term thixotropy is defined in a number of encyclopaedias but in slightly different ways of which two main views dominate. The first type of view regards the material as a concentrated gel which is transformed into a liquid when disturbed and back to a gel again at rest. The second view regards the material properties in terms of e.g. viscosity (or other rheological properties) which is increased at rest while decreasing under a constant shear stress.

The definition of thixotropy in the Swedish National Encyclopaedia, Nationalencyklopedin (1989-1996), represents the first type of definitions and reads as follows (author’s translation from Swedish):

"Property of a viscous (viscid) or gel-like product turning more liquid the longer time and the more vigorous it is deformed (e.g. by stirring). The thixotropy is caused by time and force dependant structural changes of the product. The product regains its original gel-like condition when the deformation is terminated”.

Another definition of thixotropy, representing the second way, is written in the first sentence in the introduction Chapter of Bauer and Collins (1967):

“When a reduction in magnitude of rheological properties of a system, such as elastic modulus, yield stress, and viscosity, for example, occurs reversibly and isothermally with a distinct time dependence on application of shear strain, the system is described as thixotropic”.

3.1.3 Characteristics of thixotropical materials

In principle all liquids having a microstructure can show thixotropic properties because thixotropy is merely the ability to go from one structural state to another and back again during a limited time. The driving force behind these microstructural changes is the result of the competition between the structural breakdown due to shearing forces in the flow and the structural build-up due to collisions induced by Brownian motion (see Section 2.3). The latter Brownian motion makes the particles move to as favourable positions as possible from a structure-entropy perspective.

The meaning of the concept microstructure mentioned here is often a flocculated particle system. But it could also be fibres arranging themselves favourably in the field of flow, droplets in an emulsion changing their solid geometry or molecules in a polymer solution regrouping from a tangled to a favourable system in the field of flow. The varying formations of these structural systems in different flows control both their viscosity and elasticity. The maximum structure for an emulsion is governed by the random distribution of droplets while the minimum structure is found when the distribution is as asymmetric as possible relative to the flow. For polymers it is the degree of entanglement that controls the structure. Maximum structure gives the maximum viscosity and elasticity and vice versa.

The time for structural breakdown is normally considerably shorter than the time for the structural build-up.
3.1.4 Typical thixotropic behaviour

There are a number of ways to describe the behaviour of thixotropic materials. The most suitable way is to describe the material response in shear stress ($\tau$) due to an inflicted deformation, or maybe rather, a shear rate ($\dot{\gamma}$). The following Fig 3.1 - Fig 3.4 are taken from Cheng (1987) and show the different relationships between shear rate and shear stress for thixotropic materials.

Fig 3.1 shows a test on a material that has rested for some time when suddenly it is subjected to a shear rate $\dot{\gamma}_1$. The response in shear stress will be initially high but, if the shear rate is constant, the shear stress will gradually decrease with time. If the shear rate now suddenly increases to a higher level $\dot{\gamma}_2$ the shear stress response will again be high but decrease with time. The shear stress would, if the time at constant shear rate is sufficiently long, in both cases reach the equilibrium values $\tau_{e1}$ and $\tau_{e2}$, respectively. In this case the typical thixotropic behaviour is that the shear stress (or the viscosity, $\eta$ (Pa·s), if we consider the relationship $\eta = \tau/\dot{\gamma}$) decreases at a constant shear rate.

![Fig 3.1. Stepwise increased shear rate with the material response as a reduced shear stress when the shear rate is constant, from Cheng (1987).](image)

Another way of characterising thixotropic behaviour is its ability to build up a structure at rest. In Fig 3.2 it is shown how a material after a short rest is subjected to the shear rate $\dot{\gamma}_1$ (equal to the shear rate before the rest) and how the shear stress directly increases to a peak value and then decreases down to the equilibrium value $\tau_{e1}$. If now the material is enabled to rest a slightly longer time and then subjected to the shear rate $\dot{\gamma}_1$, the shear stress reaches a higher peak level than before and with time breaks down to $\tau_{e1}$ again. The material now rests for a considerably longer time before sheared at $\dot{\gamma}_1$ and we can see that the shear stress reaches even higher peak value than previously. In other words, the level of structure in the material gets higher the longer it is allowed to rest.
A different way to characterise structural build-up is shown in Fig 3.3. In this case the material is subjected to a shear rate $\dot{\gamma}_2$ which instantly is lowered to $\dot{\gamma}_1$. From the equilibrium shear stress value $\tau_{e2}$ at the higher shear rate $\dot{\gamma}_2$ the shear stress (and thus, the viscosity) drops to a value lower than the equilibrium level $\tau_{e1}$ corresponding to the lower shear rate $\dot{\gamma}_1$. So, with time at the constant shear rate $\dot{\gamma}_1$ now a structural build-up occurs in the material to reach the equilibrium level $\tau_{e1}$.

Yet another characteristic behaviour of thixotropic materials is displayed when the shear rate is continuously increased from zero up to a certain value and then continuously down to zero again. The so-called flow-curves, up-curve going up in shear rates and down-curve going downwards, will then form a hysteresis loop, i.e., the shear stresses of the up-curve is higher than of the down-curve, see Fig 3.4. Thus, the structure that has been broken down during the increasing shear rate has not been rebuilt during the decreasing shear rate. If the procedure is repeated enough the following loops will be shifted down towards the x-axis until equilibrium level is reached. If the material now is sheared at a considerably higher level, the structure will be broken down further and if then subjected to an identical shear rate loop as before (when the equilibrium state was obtained) it can result in a so-called negative hysteresis loop, i.e., the down-curve is above the up-curve. This whole loop will then be lower than the equilibrium level. Repeating this procedure again the same equilibrium level as before will eventually be reached (but this time the consecutive loops will be shifted upwards).
3.2. Surface and colloid chemistry

Thixotropy as a concept and material characteristics are two among many subjects under the science field of rheology. Many mechanisms behind thixotropy of particle suspensions can be found in the colloidal domain which is subordinated the special science field of surface and colloid chemistry. Thus, it is here judged to be relevant with a Section on the specific conditions working in this surface chemistry dominated colloidal domain and the terminology used in this discipline.

3.2.1 Basic surface and colloid chemistry

Surface and colloid chemistry deals with the chemical and physical phenomena at the interface between different phases. In such an interface, the molecules are influenced by forces in different directions. This leads to a different composition at the interface relative to that in each of the bulk phases. Energy must be introduced in order to create an interface which leads to that the free energy of the system increases as the interface increases. This increase of energy per surface unit is called surface tension, \( \gamma \), having the unit N/m, Eriksson (1995).

A colloid is a system where one phase is dispersed in another phase for example between materials at different states of aggregation, i.e., gas/solid, liquid/solid, or between materials at the same state of aggregation such as oil/water. The dispersed phase should by definition have at least one dimension (length, width, thickness) in the range \( 1 \text{ nm} - 1 \mu\text{m} \) (i.e. between \( 10^{-9} \) and \( 10^{-6} \text{ m} \)). The reason why the size aspect is so important is the high ratio between the areas of the dispersed phase relative to its volume, i.e., the specific surface area. This area constitutes the kind of interface discussed above. The surface characteristics of this interface such as adsorption of materials and the electrical double-layer forces (see Section 2.2) affect...
the whole system’s physical properties considerably. In principle it is the material within the thickness of a molecule layer at the interface that most significantly affects the interaction between e.g. particles-particles or particles-dispersion medium in a colloidal system. Despite the large specific area of the dispersed phase the amount of added material equal to cover the boundary surface with one molecular layer is mostly relatively small. Thus, to change the physical characteristics of a colloidal system only a small amount of material acting at the interface is needed, Eriksson (1995). Compare this discussion with the very small amount of superplasticizer polymers needed to drastically change the rheology of cement paste, mortar or concrete. A visualisation of particle size contra surface area is shown in Fig 3.5.

Fig 3.5. The influence of particle size on the specific area and the relative volume of a boundary layer. From Eriksson (1995).

It is also shown how large the volume of a boundary layer with 1 nm thickness represents relative to the solid volume of a particle system depending on the particle size.

3.2.2 Interaction between particles suspended in liquids

Interparticle forces originate from the interatomic and intermolecular forces on the particle surface. Normally these forces are described in terms of intermolecular energy potential, of which the derivate is the force, i.e., a negative tangent represents attraction and a positive tangent repulsion, Cheng (1987), Shaw (1992). This energy potential has the principle shape as shown in Fig 3.6. At long intermolecular distances the van der Waals attraction dominates while at short distances it is the steep Born repulsion that dominates, originating from the overlapping electron clouds of the molecules. The potential for van der Waals attraction is proportional to $r^{-6}$ while the potential for repulsion is proportional to $r^{-12}$, where $r$ is the intermolecular distance.

By integrating the intermolecular energy potential over all molecules in a pair of particles the interparticle energy potential can be calculated.
3.2.2.1 Van der Waal forces

Van der Waals forces are always attractive, relatively long ranged and proportional to $r^{-6}$ ($r$ is the distance between atoms, molecules or particles). There are three dominating types of van der Waals forces: Keesom, Debye och London. The latter is also denoted dispersion force and is the only of these three always present (in the same way at the gravitational force), Hiemenz and Rajagopalan (1997).

Common for all these kind of interactions is that they originate from the ability of atoms or molecules to give rise to moment of dipole, either permanent or induced. In the following, the terms dipole and moment of dipole will be further explained.

Many molecules have no net charge (as in the case of ionised molecules) but are likewise able to form a dipole and are then named polar molecules, Israelachvili (1992). Examples of molecules with a permanent dipole are HCl and H$_2$O. In the case of the HCl-molecule, the chloride atom tends to pull the hydrogen molecule towards itself and creates an asymmetry between protons and electrons. The same kind of asymmetry is created in the water molecule when the two covalent bonds between the oxygen atom and the hydrogen atoms both contribute to the dipole. The explanation is that the oxygen atom has a higher electron negativity which makes the location of electrons more often closer to it. Thus, the oxygen end becomes more negatively charged while the hydrogen end is more positive. In a covalent bonding the atoms share their electrons and therefore lose the characteristics of individual atoms.

The dipole moment of a polar molecule is defined as $\mu = ql$ where $l$ is the distance between the two charges $+q$ and $-q$.

Permanent dipoles accrue only in asymmetric molecules and thus, not in single atoms. A dipole induces an electrical field (in the same way as ions) which in turn induces nearby molecules to become dipoles and thus, become induced dipoles. One can also say that the

Fig 3.6. Forces between atoms or molecules expressed as pair potential energy, $V$. From Cheng (1987).
molecule is polarised. All atoms and molecules are polarizable and their polarizability, denoted \( \alpha \), is determined by the induced dipole moment, \( u_{\text{ind}} \), acquired in the electrical field \( E \) according to \( u_{\text{ind}} = \alpha E \).

For non-polar molecules, the polarizability arises when the negatively charged electron cloud is displaced, due to an electrical field, relative to the positively charged nucleus; see the schematic illustration in Fig 3.7.

![Fig 3.7. Induced dipole in a one-electron atom.](image)

When two polar molecules come close together, a dipole-dipole interaction arises which is comparable with such that arises between two magnets. This interaction is always attractive.

The phenomena behind the three dominating types of attractive van der Waals forces are:

- **Keesom interaction** – the interaction between two permanent dipoles
- **Debye interaction** – the interaction between a permanent dipole and an induced dipole
- and finally:
- **London interaction** – the interaction between two induced dipoles.

Note that the latter interaction, the London or dispersion interaction does not need any presence of any permanent dipole (like in the case of the other two types of interactions). Instead, the attractive forces between two non-polar atoms arise due to that at any instant there is a finite dipole moment given by the electron position relative to the positive nucleus. However, the time average dipole moment is zero. This instantaneous dipole moment generates an electrical field that can polarize a nearby neutral atom and thus, induce a dipole moment and an interaction arises between the atoms, Israelachvili (1992).
3.2.2.2 The electrical double layer

The electrical double layer gives rise to repulsive forces between particles with surface charge. Such particles will attract counter-ions to the surface, see Fig 3.8, and the concentration of these counter-ions will decay with increasing distance from the surface. If the particle is forced to move in the liquid, the ions inside the so-called Stern layer will move with the particle while the ones outside this layer are left behind. The electrical charge in this layer is usually referred to as the zeta-potential, Cheng (1987), Shaw (1992), Hunter (1994).

The reason behind the repulsive forces is that when two particles get close enough to each other, their clouds of attracted ions will overlap. When this occurs, the osmotic pressure inside the ion clouds will increase and a repelling force arise.

![Fig 3.8. The electrical double layer, from Cheng (1987).](image)

3.2.2.3 Total interaction

The total interaction between particles consists of the two components: (1) van der Waal attractive forces and (2) the electrical double layer repulsive forces. When these interactions are plotted together in the same graph, it could result in the principle graph shown in Fig 3.9. Three characteristics of the total interaction at different distances between two particles are worth noting, Cheng (1987).

Let us investigate the particle interaction starting from a remote distance. First we have the interaction secondary minima at relatively long distances. This comparably low attractive interaction gives rise to what is normally referred to as flocculation. If this secondary minimum is shallow, the flocculated particles can easily be separated by a shear flow. However, if this minimum instead is deep, strong flocs can be formed. It is this kind of secondary minimum flocculation that commonly is regarded as the basis for thixotropic structures that materials (especially particle suspensions) build up at rest.

Secondly, we have the interaction primary minima at small distances. The energy potential of this attraction is strong and gives rise to coagulation which is much harder to break than flocculation.

Thirdly, in between these two primary and secondary minima, respectively, we find potential maximum, $V_{\text{max}}$, which functions as a repulsive barrier against coagulation. If the surface- or zeta-potential for the particles increases, this barrier will increase and the secondary minima are shallower.
3.2.3 Brownian motion

Thermal movements in random directions of all atoms and molecules, for example in the liquid phase of a particle suspension, will make them constantly bombard the particles in the suspension. This results in that the particles themselves increase their kinetic energy and starts to move randomly. The direction of each individual particle changes constantly and the path will be zigzag shaped. This randomised movement of colloidal particles is called Brownian motion after a botanist who discovered these movements of pollen, Barnes (1997), Cheng (1987), Hunter (1994).

One consequence of the kinetic theory is that all particles in the suspension, regardless of size, have the same average translation energy, Eriksson (1995). This is valid if no external forces act upon the particles. The magnitude of this average translation energy is, for any arbitrary particle $1/2kT$ along a given axis. Then we have: $1/2mv^2 = 1/2kT$, where

- $m$ is the particle mass in kg
- $v$ is the particle velocity in m/s
- $k$ is the Bolzmann constant, $k = 1,3805E-23$ J/K
- $T$ is the absolute temperature in Kelvin.

From this it is obvious that the particle velocity is inversely proportional to the particle mass. In other words, the translation velocity of a small particle is higher than of a bigger one (from a mass-perspective).
At the processing of ceramic powder, which is dispersed in a liquid forming a suspension, it is important to take into consideration the particle size and degree of energy necessary for structural breakdown and mixing, Pugh and Bergström (1994). The influence of particle size on type of force acting on the particles is great, which is schematically shown in Fig 3.10. Surface forces such as van der Waal forces, electrostatic forces and Brownian motion can only dominate over gravitational and inertial forces if the particle size is small enough. In Table 3.1 this size is indicated to be in the range of 0.1 μm. For bigger particles, around 1-10 μm, the gravitational and inertial forces are important and the forces arising from stirring and mixing can give the system enough energy to separate flocculated particles.

Table 3.1. Energy for particles in a suspension depending on the interaction of different types of forces. From Pugh and Bergström (1994).

<table>
<thead>
<tr>
<th>Type of interaction</th>
<th>Energy (in units of kT) for particles of given size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1 μm</td>
</tr>
<tr>
<td>van der Waals attraction</td>
<td>10</td>
</tr>
<tr>
<td>Electrostatic repulsion</td>
<td>0-100</td>
</tr>
<tr>
<td>Brownian motion</td>
<td>1</td>
</tr>
<tr>
<td>Kinetic energy of sedimentation</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>Kinetic energy of stirring</td>
<td>1</td>
</tr>
</tbody>
</table>
3.3. Measurement techniques – methodologies

To express the thixotropy of a material in absolute and fundamental terms is very difficult because the thixotropic response is strongly dependent on the material shear history. It is even stated in Tattersall and Banfill (1983) that reported results using the loop-test technique where a detailed description of how these are performed is left out is more or less worthless. Thus, the normal procedure using this kind of methodology is to perform relative measurements.

There are several methods of how to characterise thixotropy to be found in literature of which a majority is based on rheological measurements but examples of empirical methods are also reported. Among the more frequently described methods is to shear the material at constant, but different shear rates and measure the structural breakdown with time, see the example in Fig 3.11. However, the structural build-up is unfortunately seldom reported; see the discussion in the next Section.

![Fig 3.11. Structural breakdown at constant shear rate, from Tattersall and Banfill (1983)](image)

Another rheological method consists of performing a so-called “loop-test”. This means that the material is sheared with a continuously increasing shear rate and continuously down again to zero shear rate. If the material is thixotropic, the registered shear stresses for the up-curve will be higher than the stress values of the down-curve, see Fig 3.12 (see also the discussion in Section 3.1.4).

![Fig 3.12. The principle of a “loop-test”. From Barnes et al. (1989).](image)

The area between the up- and down curves (the right graph in Fig 3.12) has according to Wallevik and Nielsson (1998) the dimension “energy” in relation to the volume of the tested material indicating the energy necessary to break down the structure. However, they also
emphasise what has earlier been discussed, i.e., that this area does not represent any characteristic material property because the material’s shear history and degree of dispersing considerably influence the size of the area.

Finally, a dynamic method to measure the structure will be described, Struble and Huagang (2002), Winnefeld (2002). In this method the material is subjected to oscillating deformations (amplitudes) and thus, is subjected to oscillating shear stresses; see the principle in Fig 3.13. It is essential to perform these measurements in the so-called linear viscoelastic region where there is a linear relationship between deformation and stress in the material, i.e., the material behaves elastically. Since the deformations are small and kept within the linear viscoelastic region, it is possible to measure the degree of structure without destroying it. The quantities characterising the material are:

Storage modulus = $G'$, represents the elastic (reversible) response of the material and:
Loss modulus = $G''$, represents the viscous, liquid-like, (irreversible) response.

It is from the phase (loss) angle $\delta$ these two modules can be separated where:

- $\delta = 0^\circ$ equals to a totally elastic material
- $\delta = 90^\circ$ equals to a totally viscous material
- $0^\circ < \delta < 90^\circ$ represents a viscoelastic material

The relation between $\delta$, $G'$ and $G''$ is: $\tan \delta = G''/G'$

![Fig 3.13. The principle of a dynamic (oscillating) measurement.](image)

### 3.4. Controlling thixotropy

#### 3.4.1 Additives – paint

Thixotropic paints have been known for many years and the advantages with the thixotropic properties are many, Shaw (1992), Hunter (1994), Pierce (1969), Rees (1995), Barthel et al. (2002). The pigment suspension is improved; the paint becomes non-dripping, is more easily spread on surfaces and covers sharp edges better. In addition, the thixotropy of the paint contributes with resistance to segregation without limiting the self-levelling ability. On top of this it gives significantly improved transport stability, see Fig 3.14. Thus, there are many advantages in making the paints thixotropic. But it is important to choose the right kind of additives to avoid that some other properties of the paint are worsened.
Fig 3.14. The primarily desired properties visualised. The left figure shows the result of making the paint drip-free (right part). The right figure shows how the stability increases with increasing dose of thixotropy additive. From Kusumoto Chemicals Ltd (2006).

Regardless of admixture type to increase the thixotropy, they must function by forming a relatively loose three-dimensional structure, a structure which must be easily broken when the paint is stirred or applied on a surface. In both cases the shear rate is increased and the structure breaks. Some typical materials used to make paints thixotropic are shown in Fig 3.15 and Table 3.2. The thixotropy additives are normally divided into inorganic and organic types. The first example in Fig 3.15 is inorganic clay minerals. These materials have in common that the small clay particles often have the shape of plates of which the edges is negatively charged while the surfaces are positively charged and thus, attract each other forming card-house like structures, Bakker et al. (1999).

Fig 3.15. Some typical materials used to give paint thixotropic properties; clay particles, waxes and silica. From Kusumoto Chemicals Ltd (2006).

This is especially pronounced for different bentonite clays, Shaw (1992). Another example is different waxes of which the particles swell and form a structure, Bakker et al. (2002). A third example is colloidal silica which also has the ability to form loose three-dimensional structures, Hunter (1994), Barthel et al. (2002).
Table 3.2. Inorganic and organic types of thixotropy controlling additives for paint and their primary mechanisms. From Kusumoto Chemicals Ltd (2006).

<table>
<thead>
<tr>
<th></th>
<th>How to work</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inorganic</td>
<td>Fine colloidal dispersion</td>
<td>Colloidal silica, Organo bentonite Calcium carbonate</td>
</tr>
<tr>
<td>Organic</td>
<td>Network structure made with swollen particles</td>
<td>Hydrogenated castoroil Amide wax Metal soaps Solbitoles</td>
</tr>
<tr>
<td></td>
<td>Network structure with swollen particles and pigment</td>
<td>Oxidised polyethylene waxes Polymerized vegetable-oils</td>
</tr>
<tr>
<td></td>
<td>Network structure formed by flocculation with pigment</td>
<td>High alcohol sulfonate polyester of dimers etc.</td>
</tr>
</tbody>
</table>

An illustrative example of how the thixotropy of paint can be controlled to reach the exact balance between different mechanisms is reported in Rees (1995). The principle of how the viscosity of alkyd based paint is changed can be described with the model showed in Fig 3.16. It is shown how the thixotropy controlling additive (a modified polyamide) is bound to the alkyd chains and at rest, entangles randomly. The amide groups are bound to the alkyd backbone and through hydrogen bonds between themselves (see Fig 3.17); they impart thixotropy and a gel like consistency to the paint. When the brush is inserted into the paint, the hydrogen bonds are stretched (right part of the figure) and are broken when the paint is spread with the brush (often at shear rates up to $10^3$ (s$^{-1}$) and higher, (Pierce (1969) and Rees (1995), they break completely. The alkyd chains are now stretched (lowest part of figure) and the paint gets a liquid-like consistency. When the brush leaves the paint in an un-sheared condition, the polymers start to entangle again (left part of the figure). The balance between stability against segregation and self-levelling ability is governed by the rate with which the structure is regained when being able to rest.

![Fig 3.16. Model for thixotropic behaviour. From Rees (1995).](image)
It is shown in Fig 3.18 how the desired characteristics of paint can be measured with dynamic measurements (see Section 3.3). Paint No. 1 has the longest linear viscoelastic region making it difficult to break the hydrogen bonds and the paint is thus, difficult to apply. Paint No. 2 however, has the shortest linear viscoelastic region making it easy to apply but also more viscoelastic with increasing risk for flocculation of pigment. Consequently, in this case the linear viscoelastic region for paint No. 3 is found most suitable.

3.4.2 Additives – cementitious systems

There is not so much information or reports to be found on thixotropy controlling admixtures for cement based systems. However, in Khayat et al. (2002) it is reported on a product, propylene carbonate (denoted PPC) that has been used in an investigation as such a thixotropy controlling admixture. This product is a cyclic organic carbonate that is water soluble up to equally an 8 % solution. In the alkaline water of a cement based system, the PPC undergoes a chemical reaction and forms rapidly propylene glycol and carbonate anions. At normal temperatures in mortar and concrete applications the half-time for the alkali hydrolyses of PPC is less than a minute. The hydrogens on the propylene–glycol-hydroxyls can form hydrogen bonds between themselves and this mechanism together with the interaction between carbonate and cement particles explain the thixotropic effect in concrete. The results show that PPC strongly influenced the tested mortars’ thixotropy but on the expense on a higher superplasticizer demand.
It is also indicated in Assaad et al. (2003b) that viscosity modifying admixtures can contribute to a thixotropic behaviour, but not to such degree that they could be regarded as thixotropy controlling.

In Allan (1997) it is stated that latex influences the thixotropy and results from tests performed on mortar are reported.

Not so very surprisingly there is information to be found where the influence of superplasticizers on the thixotropy is discussed, but then exclusively on how the thixotropy is decreased due to the superplasticizer molecules dispersing and stabilising mechanisms, i.e., how the range of attractive forces are over-bridged, Ur'ev et al. (1997).

### 3.5. Thixotropy of cementitious materials

#### 3.5.1 Cement paste, fine and micro mortar

Most reports dealing with cement paste thixotropy mean that the initial and relatively strong structure of aggregated or flocculated cement particles after shearing (structural breakdown) does not regain its shape, Ish-Shalom and Greenberg (1962), Lapasin et al. (1980 and 1983). In other words should this process not be reversible but instead describing that cement paste is a "partially thixotropic" material. The principle of this statement is schematically described in Fig 3.19, Tattersall and Banfill (1983), and is based on the assumption that cement particles already before they come into contact with water are flocculated due to weak surface forces. At contact with water a membrane is formed around the floc which leads to a stronger bond between the particles. When the paste is sheared (either when mixed or during rheological testing) these membranes can break and the particle be separated. If this happens the unhydrated cement surfaces is exposed and a new membrane is instantly formed. When the shearing decreases and the particles again are able to floc under influence of van der Waal forces there are no unhydrated surfaces left. Thus, the original structure cannot be rebuilt but instead a weaker structure.

![Fig 3.19. The principle behind an initial structure of flocculated particles not being rebuilt after structural breakdown. Thus, the process is said to be irreversible. From Tattersall and Banfill (1983).](image)

When this phenomenon is studied using a rheological procedure where the paste is sheared in an up-down loop, see Fig 3.12, it results in the characteristic discrepancy between the (up and down) flow curves which is interpreted as a thixotropical behaviour. This behaviour should not be explained as thixotropical but instead as a shear induced reduction of yield stress. The definition of thixotropy states that the process is reversible.
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Results from tests on cement paste where different superplasticizers (SP) are evaluated are reported in Wallevik and Iversen (1997). The Icelandic cement used contains 7% silica fume and is relatively water demanding. The W/C ratio was kept constant at 0.30 and the pastes were tested in a Bohlin V88 6 and 18 minutes after mixing, respectively. The results are shown in Fig 3.20 of which the leftmost chart represents results where the melamine based superplasticizer Melment L10 is tested at the dose 2.9%. This result is reported to support the fact that this SP normally contributes with a poor open time. But if stirred before, it does not lose the workability to any significant degree which is an obvious thixotropic behaviour. In the middle left part of Fig 3.20 the results are shown from tests where the naphthalene based SP Mighty 150 is used. The great plasticizing effect leads to a yield stress close to zero but also to a very small degree of thixotropy.

The middle right chart in Fig 3.20 shows results where a lignosulphonate SP (with high purity from calcium) is tested in combination with the naphthalene based SP Addition 630 and Mighty 150. It is indicated that the lignosulphonate based additive increases the thixotropy slightly. In the rightmost chart in Fig 3.20 the result are shown where Mighty 150 is tested in combination with the lignosulphonate SP and an air entrainer Amex 3000 (the upper curve). The result was a high yield stress and a certain but rather unclear thixotropy. The two lower curves represent this combination of admixtures but with an extra dose of Melment L10 added 15 minutes after mixing. The thixotropy is now significant and favourable in that the segregation of particles is hindered when the suspension rests.

This investigation was not primarily performed in order to evaluate the thixotropy but is nevertheless interesting because it shows that chemical admixtures (in this case not viscosity enhancing admixtures) do indeed have an impact on the thixotropical behaviour.

Another interesting study, Lapasin et al. (1983), reports on the influence of interparticle distances in cement paste on the “breakdown work” needed to break down a structure to an equilibrium level. In this report cement paste is regarded as a partially thixotropic material and thus, the structural build-up is neglected. The work necessary to break down the structure is calculated from the area between the curve representing an undisturbed structure (i.e., the \( T_0 \)-value in Fig 3.11) depending on the shear rate and the curve representing the equilibrium structure (i.e., the \( T_E \)-value in Fig 3.11). An example of these curves is shown in Fig 3.21. Cement pastes where cements having different specific surfaces (according to Blaine) and with different W/C were tested in a Rotovisco-Haake RV11. Different specific surfaces and
different W/C result in a broad range in terms of the distance parameter, $d$ (kg/m²), in the cement pastes. This distance parameter is in Lapasin et al. (1983) calculated according to:

$$d = \frac{W/C}{SSB},$$

where:

$W/C = \text{water to cement ratio (-)}$.

$SSB = \text{specific surface according to Blaine (m}^2/\text{kg}).$

**Fig 3.21.** The difference between shear stresses for undisturbed structure and equilibrium structure depending on shear rate denoted ”breakdown work”, $A_b$, (left) and how this work is dependent of inter particle distance, $d$, in the paste (right). From Lapasin et al. (1983). The shading of the area $= A_b$ is done by the author.

The right side chart in Fig 3.21 shows that the work needed to break down the structure depends strongly on the distance parameter. Decreasing distances leads to increased work and the breakdown kinetics slows down.

The influence of time after mixing on the size of the area between registered up- and down curves is reported by Caufin and Papo (1984) and the principle shape of these hysteresis loops are shown in Fig 3.22. The figure shows also how sensitive this method is to the configuration of the shear rates. Even if the shearing starts at zero and turns at the same shear rate, a difference in the acceleration upwards and downwards will result in different registered values of the up- and down curves and thus, in the area between them. The viscometer used is a Haake rotovisco RV3.
Fig 3.22. Influence of shear acceleration on the shape of the hysteresis loop. From Caufin and Papo (1984).

An example of how the breakdown area varies with increasing time after mixing is shown in Fig 3.23 which also displays that the rheology is close to constant up to 2 hours after mixing and then the yield stress increases due to cement hydration. The shear acceleration 2.9 s\(^{-2}\) and maximum shear rate 325 s\(^{-1}\) were used. Every new test was performed on an untested paste.

Fig 3.23. Area between up- and down curve with time after mixing (upper chart) and corresponding yield stresses, \(\tau_0\), and maximum shear stress, \(\tau_{\text{max}}\) (lower chart). From Caufin and Papo (1984).

By Ish-Shalom and Greenberg (1962) a Haake Rotovisco was used to measure the rheology of cement pastes with cement containing different amounts of C\(_3\)A, see Table 3.3. W/C was kept constant at 0.5.
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Table 3.3. The different cements used by Ish-Shalom and Greenberg (1962).

<table>
<thead>
<tr>
<th>Composition, percent</th>
<th>A 15096 (C 2.2.7) Type I normal (clinker)</th>
<th>B 15097 (C 10.2.3) no gypsum</th>
<th>C 15098 (C 12.2.3) Type I external</th>
<th>D 15099 (C 14.2.3) Type IV low heat</th>
<th>E 15022 A (C 13.2.3) Type II moderate heat</th>
<th>F 19648 (C 15.2.2) zero C_3A</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_3A</td>
<td>44.8</td>
<td>45.4</td>
<td>45.3</td>
<td>40.0</td>
<td>68.2</td>
<td>66.0</td>
</tr>
<tr>
<td>C_3S</td>
<td>26.9</td>
<td>28.5</td>
<td>28.6</td>
<td>64.2</td>
<td>76.5</td>
<td>14.7</td>
</tr>
<tr>
<td>C_2S</td>
<td>1.57</td>
<td>1.59</td>
<td>1.56</td>
<td>0.61</td>
<td>1.73</td>
<td>4.5</td>
</tr>
<tr>
<td>C_3AF</td>
<td>6.7</td>
<td>6.6</td>
<td>7.6</td>
<td>5.9</td>
<td>12.9</td>
<td>12.9</td>
</tr>
<tr>
<td>C_S</td>
<td>11.6</td>
<td>11.3</td>
<td>9.8</td>
<td>2.3</td>
<td>4.4</td>
<td>0.0</td>
</tr>
<tr>
<td>C_3A(SO_4)</td>
<td>3.3</td>
<td>0.7</td>
<td>3.9</td>
<td>3.1</td>
<td>2.7</td>
<td>4.30</td>
</tr>
<tr>
<td>Free CaO</td>
<td>2.5</td>
<td>2.63</td>
<td>3.4</td>
<td>1.72</td>
<td>1.44</td>
<td>0.69</td>
</tr>
<tr>
<td>Total alkalis (Na_2O+K_2O)</td>
<td>0.33</td>
<td>0.33</td>
<td>1.37</td>
<td>0.37</td>
<td>0.22</td>
<td>0.12</td>
</tr>
<tr>
<td>Surface area, m^2/g (Wagner turbidimeter)</td>
<td>2,250</td>
<td>1,500</td>
<td>2,250</td>
<td>2,280</td>
<td>2,200</td>
<td>2,460</td>
</tr>
</tbody>
</table>

The results shown in Fig 3.24 indicate the strong influence of the amount of C_3A in the cements on the thixotropical properties with time after mixing. The methodology used is the same as in the previous example, i.e., the loop-test with calculation of the area between the up- and down curve.

![Fig 3.24. Different thixotropical response depending on the amount of C_3A in the cement and the time after mixing. From Ish-Shalom and Greenberg (1962).](image)

The explanation of this significant difference in rheological behaviour (increase of yield stress, plastic viscosity and thixotropy) is, according to Ish-Shalom and Greenberg (1962) that the hydration product of the C_3A clinker, i.e., ettringite needles, forming a structure in the paste. According to Fig 3.24 it is clear that hardly any changes occur until 45 minutes after mixing. At the next time of measurement, 2 hours, the dependence of the amount of C_3A is high. This development increases further after another hour at rest.

They also confirm that the relative increase of cement fineness affects the rheology in terms of increased yield stress, plastic viscosity and thixotropy.
Viscosity modifying agents (VMA) are in many cases used today to enhance the stability for self-compacting concrete but also for other purposes such as shotcrete, underwater concrete or to enhance the pumpability of concrete. The influence of such a product on the time dependant structural build-up of cement pastes has been evaluated by Ghio et al. (1994). The tested product is a polysaccharide polymer with a high molecular weight (approximately 2 million amu (atomic mass unit)) but no other description of this product is mentioned. The type of viscometer used is neither described besides that the sensor system consists of concentric cylinders. The VMA increases the viscosity of the cement pastes with time already from the time just after mixing as shown in Fig 3.25. The viscosity of the cement pastes without any VMA is not changed during the duration of the tests (35 minutes). It is, however, reported that if the cement pastes were mixed again after resting, they regained the initial viscosity which indicates that the process is rather of physical nature than of chemical nature (cement hydration).

Fig 3.25. Increase in viscosity with time for cement pastes with and without VMA, respectively. From Ghio et al. (1994).

The methodology named “creep/recovery” has been used in a systematic series of tests where the aim was to measure how the yield stress of cement pastes increases with time up until the setting time, Struble and Lei (1995). The principle is to apply a constant stress to the tested material and measure the creep strain (in this case for 30 seconds) and then release the stress and measure the recovery strain (also this for 30 seconds). The purpose was to measure the increase of yield stress without breaking down the structure during the measurements. By carefully studying different pastes at different hydration ages according to the principle shown in Fig 3.26 the measurements could thereafter be performed on a single paste.
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Fig 3.26. The result of a creep/recovery measurement. In this case the yield stress has been exceeded which is shown by the fact that a deformation remains when the stress is removed (the right part of the curve). From Struble and Lei (1995). Compliance (1/Pa) is the strain divided by stress.

The results are shown in Fig 3.27 and Fig 3.28. The curve representing the yield stress follows basically the shape of that of the one which was obtained using a vicat needle and thus, no structure other than that caused by hydration has been able to be detected. This can only be interpreted as that no thixotropical, reversible structure, has been measured. Yet, every possible measure has been taken to avoid breaking the structure, i.e., the pastes has been at rest during the full time of the measurement. The drop to zero stress at approximately 150 minutes indicates that the yield stress was exceeded and thus, the structure was broken and started to grow again. The difference in W/C is shown in Fig 3.28 and because of natural reasons the paste with the lower W/C 0.40 binds earlier than the one with W/C 0.45.

Fig 3.27. Time development of the paste yield stress. Circular dots show sequential measurements on a single specimen while triangular dots represent measurements of different pastes at different times of hydration. From Struble and Lei (1995).
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Fig 3.28. Time development of the yield stress of paste with different W/C ratios. From Struble and Lei (1995).

Results from an interesting investigation are reported in Winnefeld (2002) and deal with tests on cement paste using dynamic measurements, i.e., with oscillating deformation and stress response.

As discussed earlier in Section 3, the tests started by seeking for the linear viscoelastic region for the pastes to be incorporated in the investigation. These results are shown in Fig 3.29 and are obtained by performing a strain-sweep measurement using a constant frequency (in this case 0.40 Hz) and continuously increasing the amplitude from as small values as possible to higher.

Fig 3.29. Strain sweep measurement in order to find the linear viscoelastic region. From Winnefeld (2002).

The limit for the linear viscoelastic region is at the amplitude where both the storage modulus ($G'$) and the loss modulus ($G''$) decrease. In this case it was found to be at the amplitude
(strain) $\gamma = 6 \cdot 10^{-5}$ (equals to $5 \mu$rad), a value which also is supported by others saying that generally the upper value of the linear viscoelastic region is around $10^{-4}$, Powers (1968).

The amplitude equal to $\gamma = 5 \cdot 10^{-5}$ was used throughout the rest of the investigation. A first test was performed using a paste with W/C of 0.40 and the result according to Fig 3.30 was obtained. An analysis of the result shows some interesting facts. First, both $G'$ and $G''$ increase rapidly the first time after the start of the measurement and this is attributed to the thixotropic structural build-up when the particles flocculates after the mechanical breaking of the structure during the mixing process.

![Graph](image-url)  

**Fig 3.30. Structural build-up of paste expressed with $G'$, $G''$ and $\tan(\delta)$. From Winnefeld (2002).**

Secondly, the value of $\tan(\delta)$ being close to 1 directly after mixing indicates that the cement paste behaves like a material with combined and equal solid and liquid like properties. After approximately 30 minutes the slope of the curves decreases and the increase rate becomes more constant up until 100 minutes. The explanation is that the cement slowly hydrates during this time. But after this period the hydration starts considerably.

This investigation was primarily aimed at focusing on the structural build-up of cement paste due to cement hydration and how this is influenced by different admixtures up until the time of setting. Common for all results when admixtures are added is that an increasing dose increases the retardation. Such results are shown in Fig 3.31 when a superplasticizer based on poly carboxylate ether (PCE) is used.
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This generation of superplasticizers is frequently used for self-compacting concrete to enhance the open time and the results support this effect. The retardation is considerable for this kind of PCE superplasticizer, also in comparison to naphthalene and lignosulphonate based products. If the focus is set on the thixotropical structural build-up the first 30 minutes, clear differences between the pastes storage modulus, $G'$, is displayed as shown in Fig 3.32 (which by the author is zoomed from Fig 3.31). Not only the setting time is affected by increasing SP dose but also the ability of the particle system to reflocculate after the mechanical structural breakdown during mixing. The active PCE polymers work with steric hindrance mechanism and the range of the interaction forces, schematically shown in Fig 3.9 Section 3.2.2.3, are bridged over by the large molecules hindering the particles to come as close together as the secondary minimum.

Even though not dealing with the flocculation mechanisms at rest the comprehensive dissertation by Jon E. Wallevik, see Wallevik (2003), is very interesting in that he manages to describe the steady state and transient behaviour of fresh cement pastes, measured in a ConTec 4 viscometer, mathematically. The numerical modelling he uses is derived from a nearly complete physical description of the flocculation and dispersion mechanisms of cement particles. To account for the flow history of the paste, fading memory integrals are used. The model is based on, and thus, a further development of the famous Hattori-Izumi theory (as described and referred to by Wallevik (2003)).
3.5.2 Conventional concrete and SCC

It is stated by Hu and Larrard (1996) that concrete indeed is a true thixotropic material because in the process where structural breakdown occurs during constant shear rate this is followed by a structural build-up when the concrete rests. In other words the thixotropic process is also to be regarded as reversible. In addition to this, the authors state that experience shows that this time-dependent structural build-up happens in a few minutes at rest. From a practical point of view the thixotropy increases considerably the concrete yield stress during rest and the authors differ between a resting shear yield stress, $\tau_{r0}$, and a shear yield stress, $\tau_0$. It is $\tau_{r0}$ that after a period at rest makes it possible for the concrete to, for example, hold a slope without flowing or be deformed. The results in Table 3.4 show that the resting shear yield stress can be several times higher than the shear yield stress.

Table 3.4. Comparison between resting shear yield stress, $\tau_{r0}$, and a shear yield stress, $\tau_0$, for the same concretes with and without vibration, respectively. From Hu and Larrard (1996).

<table>
<thead>
<tr>
<th>without vibration</th>
<th>under vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_0$ (Pa)</td>
<td>$\tau_{r0}$ (Pa)</td>
</tr>
<tr>
<td>b46</td>
<td>361</td>
</tr>
<tr>
<td>b49</td>
<td>309</td>
</tr>
<tr>
<td>b x 1</td>
<td>1500</td>
</tr>
<tr>
<td>b45</td>
<td>-</td>
</tr>
</tbody>
</table>

An example where the rheology measurement displays the thixotropical behaviour is shown in Fig 3.33. The clear sign of the structural build-up occurring during the first minutes at rest is that the registered torques, $\Gamma$ (Nm), at the three lowest shear rates are higher than the straight line representing the Bingham model. After that a number of measurements are done at low shear rates where the structural build-up is clearly shown (filled symbols).

Fig 3.33. Rheology measurement where the thixotropy is clearly displayed, Hu and Larrard (1996).

A different approach to characterise and quantify the thixotropic properties of full flow and self-compacting concrete is reported by Assaad et al. (2003b). Mix designs for the three series of tested concretes are listed in Table 3.5. In the first series silica fume has been added to the
cement and in the second series fly ash is added to those in series 1. The concrete in both these series are self-compacting while for series 3 the concrete is of full flow consistency with silica fume added. In the first two series both accelerating and retarding admixtures are added, respectively. In the third series the concretes have been mixed with retarder and both with and without a viscosity modifying additive, respectively.

Table 3.5. Mix designs for tested concretes, Assaad et al. (2003b).

<table>
<thead>
<tr>
<th>Mixture codification</th>
<th>Type of binder</th>
<th>Type of binder</th>
<th>Type of binder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4% SF + 96% C</td>
<td>6% SF + 22% FA + 72% C</td>
<td>8% SF + 92% C</td>
</tr>
<tr>
<td>SCC-SF-ACC</td>
<td>225</td>
<td>225</td>
<td>450</td>
</tr>
<tr>
<td>SCC-SF-C</td>
<td>225</td>
<td>225</td>
<td>189</td>
</tr>
<tr>
<td>SCC-SF+FA-ACC</td>
<td>--</td>
<td>--</td>
<td>189</td>
</tr>
<tr>
<td>SCC-SF+FA-RET</td>
<td>450</td>
<td>450</td>
<td>189</td>
</tr>
<tr>
<td>SCC-SF+FA-RET</td>
<td>--</td>
<td>--</td>
<td>189</td>
</tr>
<tr>
<td>SCC-SF+FA-RET</td>
<td>--</td>
<td>--</td>
<td>189</td>
</tr>
<tr>
<td>SCC-SF+FA-RET</td>
<td>--</td>
<td>--</td>
<td>189</td>
</tr>
<tr>
<td>SCC-SF+FA-RET</td>
<td>--</td>
<td>--</td>
<td>189</td>
</tr>
<tr>
<td>SCC-SF+FA-RET</td>
<td>--</td>
<td>--</td>
<td>189</td>
</tr>
<tr>
<td>SCC-SF+FA-RET</td>
<td>--</td>
<td>--</td>
<td>189</td>
</tr>
</tbody>
</table>

The measuring principle shown in Fig 3.11 is used to characterise the thixotropy, i.e., to measure how the shear stress decreases with time at a constant but different levels of shear rate, respectively, see Fig 3.34. Two values are measured at each level of shear rate, i.e., the initial shear stress and the equilibrium shear stress and if the curves formed by these values, respectively, we get the principle result as shown in Fig 3.35. The area between these two curves corresponds to the area obtained using loop-test, see Fig 3.12. The concrete structure broken down is expressed in J/m³, i.e., energy per volume concrete.

![Fig 3.34. Structural breakdown at different shear rates. From Assaad et al. (2003b).](image)
Fig 3.35. Principle for how the breakdown area between the initial shear stresses and the equilibrium shear stresses is calculated. From Assaad et al. (2003b).

The described technique was used when testing the concretes listed in Table 3.5 and a typical result representing the mix with silica fume and retarder compared to the one with fly ash added is shown in Fig 3.36. The filled bars represent the initial shear stress values and the unfilled bars the equilibrium values.

Fig 3.36. Initial shear stresses (filled bars) and corresponding equilibrium shear stresses (unfilled bars) for retarded concretes without fly ash (left) and with fly ash (right). From Assaad et al. (2003b).

The result show that if a part of the binary cement (Portland cement + silica fume) is replaced by fly ash, the thixotropy is increased due to the increased specific surface of the particle system. According to Vom Berg (1979) and Billberg (1997), both the yield stress and the viscosity increase when the fineness of the particle system increases. Thus, the initial shear stresses for the concretes with fly ash (SCC-SF-FA) increases due to an increasing degree of inter particle contacts (bonds). An increase in thixotropy for the concretes with accelerators...
relative to those with retarder is due to that the hydration products grow much faster when an accelerator is used. Finally, the increased thixotropy when the viscosity modifying admixture is used is because the long polymer chains form a network which not only increases the viscosity but also forms a structure through, e.g., entanglement, Assaad et al. (2003b).

3.6. Form pressure when using SCC

3.6.1 Reported form pressure measurements

In Chapter 1, the development of SCC around the world was discussed as well as the increased interest in the form pressure exerted by SCC from the late nineties until today. A number of reports on this topic can be found, also besides those reported at the RILEM symposia, and the approach is somewhat varying. In some cases the focus has been set on merely measuring the form pressure without elaborating further on the governing mechanisms, Ikäheimonen (1998), Lindquist (1999), Glavind and Frederiksen (2001), Leemann and Hoffmann (2003) and Braam (2002). Others have focused more on different mechanisms such as the material thixotropic properties, Billberg and Österberg (2002), Assaad et al. (2003a), Assaad (2004), Khayat (2005), Billberg (2003) and Billberg (2006) and/or the friction between the concrete and the formwork, Vanhove et al. (2004), Ovarlez and Roussel (2006) and Graubner and Proske (2005). The latter approaches represent more theoretical aspects such as silo pressures exerted by granular materials where the Janssen model is the basis for the theories, see Section 3.6.3.

Some examples of form pressure, measured using SCC, are shown in Fig 3.37 and display the broad variation of results in terms of the relationship between casting rate and the form pressure relative to the hydrostatic pressure.

Fig 3.37. Examples of reported form pressure when using SCC (refs. shown in the figure).

These parameters are chosen since the casting rate indirectly is related to the time concrete is at rest in the formwork which is getting more and more accepted as a parameter influencing...
the pressure because of the change of concrete internal structure which increases with time. It is worth noting here that the broad varieties of results are not so surprising since the tradition of designing SCC (and of course conventional vibrated concrete) differs from country to country all over the world as described by Wallevik (2005). The use of fine powders or viscosity enhancing agents to increase the stability, the W/C ratio, superplasticizer type and dose, cement type, the aimed consistency (flowability) – all these different materials and design approaches will definitely have different impact on both the reversible structural change (i.e., thixotropy) and the irreversible ditto (i.e., rate of slump loss with time).

The left part of the graph in Fig 3.37 seems logic in that the pressure is fairly proportional to the casting rate. The pressure increases up to approximately 70 % of the hydrostatic for casting rates up to 2 m/h followed by a slower increase at casting rates up to approximately 10 m/h. From this perspective, the most surprising results are those of casting rates approximately from 20 m/h and upwards showing pressures below 70 %. The three results from Graubner et al. (2002) are strongly influenced by the slump-flow which with decreasing values (750, 710 and 610 mm) correlates to a decreasing pressure. The result at 25 m/h reported by Vanhove and Djelal (2002) is even pumped from bottom of formwork and upwards which by most hypotheses would disturb the concrete throughout the whole height of the form and thus, lead to hydrostatic pressure (if not higher if the pump pressure is added).

In Brite EuRam (2000) (see also Chapter 1), besides many aspects of production and execution of SCC also the form pressure was studied. Measurements were performed both by NCC in Sweden and by GTM in France and somewhat different conclusions were drawn. For eight trials, NCC used a common type of house wall formwork with the geometry 0.16, 2.65 and 5.7 m (thickness, height and length) and in addition two walls with increased heights; 5.3 and 8 m, respectively. The same mix was used at all ten trials having slump-flow values of 620-780 mm. The results showed that the pressures were significantly lower than the hydrostatic pressure and even so for the higher walls where the casting rate was 120 m/h. For the 5.3 m wall the pressure at the bottom of the formwork was only 59 % of the hydrostatic and for the 8 m wall even less: 29 %. GTM used various form geometries: length 1.25 or 2.5 m, height 2.8 or 5.6 m and thickness 0.2 or 0.4 m. The concrete was either mixed with VMA or with powder (two ways of stabilizing SCC mixes) and the slump-flow values ranged from 700 to 880 mm. Also casting techniques were varied between pumping and pouring using a concrete scip and the casting rates were varied between 10 and 150 m/h. The conclusion was that the pressure for most mixes was close to hydrostatic but in general, the pressure was higher when the VMA was used and when the SCC was pumped rather than poured (form filling from top in both cases).

Alfes (2004) reports that SCC with slump-flow value of 770 mm was used to fill the 110 mm space in an 2.3 m high element where the formwork consisted of stay-in-place concrete shells (50 and 60 mm thick, respectively) held together with lattice girders with 300 mm spacing distance. The pressure was measured using pressure probes fitted 100 mm from the bottom. Using as high casting rate as 132 m/h the pressure was found to be only 76 % of the hydrostatic pressure. The hypothesis behind this reduced pressure is that the humidity transport from the fresh SCC into the shells (even though wetted before casting) increased the friction and thus, the SCC could carry its own weight to such degree that the pressure deviated from hydrostatic.

The influence of casting method (pouring from above or pumping from below), workability and of mix design on formwork pressure was investigated by Leemann et al. (2006). The SCC
pumped from below with 2.0 MPa pump pressure in a 4.7 m high wall resulted in hydrostatic pressure at the top but 10 % above hydrostatic pressure at the bottom of the formwork. The pump pressure increased the hydrostatic pressure up to 1.3 m above the inlet. Three mixes with different workability values in terms of slump-flow (570-660 mm) and flow time in the L-box (2.0-6.1 s) were cast from the top in a 2.7 m high form. The pressure was found to be 87-90 % of the hydrostatic pressure for all of the mixes and thus, indicated that the workability had no significant influence. Other trials using a 0.975 m high form indicated that: (1) a slight disturbance of the filled form increased the pressure (from 10 % to 70 % of maximum pressure) as long as after 2 hours after finished casting, (2) increasing particle fineness increased the rate of decreasing pressure after finished casting, (3) an increase of water to cementitious ratio increases interparticle distances and decrease the required amount of superplasticizer. The latter consequence, i.e., a lower degree of dispersion was found to dominate (increase) the rate of decreasing pressure after finished casting relative to the influence of particle distances. The two latter results regarding particle fineness, dispersion and interparticle distances indicate the role of these parameters on the thixotropic structural build-up (author’s comment).

The influence of section width of the form on the lateral pressure was studied by Khayat et al. (2005). SCC with 490 kg/m³ of binder, water to cementitious ratio, w/cm, equal to 0.38 having a slump-flow value of 650 mm and an air content of 6.1 % was used. Formwork (tubes) with diameters of 200 and 920 mm, respectively, was used at a casting rate of 10 m/h. The result showed that the initial pressure was slightly higher for the wider form (99 % of hydrostatic pressure) than for the narrower one (96 %) which can be explained by the arching effect which is more pronounced in the narrower form. But even more interesting is the development of decreasing pressure with time which showed to be faster for the wider form (5.3 kPa/h) than for the narrower form (3.3 kPa/h). The need for further research on this topic is emphasised by Khayat et al. (2005). Might this be due to the possibly higher temperature developed in the wider tube containing a larger mass of concrete (author’s comment)?

3.6.2 A rheological approach to the mechanisms behind SCC vs. form pressure

Besides the work performed by the author reported in this thesis, the extensive project reported as a doctoral thesis by Assaad (2004) has dealt with the thixotropic properties of SCC and its influence on form pressure and will be the one referred to hereafter in this Section.

The investigation focused on the following parameters: set-modifying admixtures, coarse aggregate characteristics, type and content of binder, type and dose of viscosity modifying admixtures (VMA), type of superplasticizer, water to cementitious ratio (w/cm), consistency and finally concrete temperature. However, only the relation between thixotropy and form pressure will be referred to here. The method described in Section 3.5.2 and showed in Fig 3.34 and Fig 3.35 (and discussed also in Section 3.3 and Fig 3.11) was used to characterise the thixotropy of totally 70 SCC mixes all having slump-flow values of 650 ± 15 mm, temperature of 20 ± 3 °C, densities of 2200 ± 200 kg/m³ and air contents of 7 ± 2 %, respectively. Three parameters were identified as the most important regarding prediction of form pressure; (1) the maximum initial lateral pressure directly after finished casting which is the design load for the form, (2) the rate of pressure drop with time which is important for planning subsequent lifts particularly important for high and voluminous castings and (3) the time before pressure cancellation which determines the time for formwork removal. The casting rate was chosen at 10 m/h for all 70 trials. The pressure directly after casting is
Chapter 3. Literature survey

represented by a value $K_0$ in % of the hydrostatic pressure and subsequently, $K_{100}$ and $K_{200}$ represent these values after 100 and 200 minutes, respectively. The thixotropy was characterised by the breakdown area (as shown in Fig 3.35) at three times; 0-30, 60-90 and 120-150 minutes, designated $A_{b1}$, $A_{b2}$ and $A_{b3}$, respectively. The time zero is the time when the viscometer bowl was filled, which was done 7 minutes after the first contact between cement and water and the time spans of 30 minutes is due to that the characterisation of the breakdown area takes 30 minutes to complete.

From all these 70 pressure and thixotropy measurements, the following models for estimating lateral pressure at different time intervals were developed:

$$K_0 = -0.047 \cdot A_{b1} + 105.8, \quad K_{100} = -0.099 \cdot A_{b2} + 112.2$$

and

$$K_{200} = -0.125 \cdot A_{b3} + 116.8,$$

see also Fig 3.38.

![Fig 3.38. Relations between breakdown areas at different times and K-values, Assaad (2004).](image)

Assaad (2004) also found that there was a relation between $A_{b1}$, and respectively $A_{b2}$ and $A_{b3}$, see Fig 3.39. Thus, it was concluded that the development with time was possible to predict just from the first thixotropy measurement after mixing.

![Fig 3.39. Relations between breakdown areas at different times after mixing, Assaad (2004).](image)
It was also recognised that the change in time-dependent structure of SCC is due to an irreversible change in terms of slump-loss and a reversible change due to thixotropy. However, only the slump-loss development is not enough to explain the development of form pressure.

Finally, for those interested in this extensive investigation it could be recommended to also read the paper by Khayat (2005) to get a good introduction. But of course all the background information, discussions and statistical valuations of the models are found only in Assaad (2004).

3.6.3 A physical approach to the mechanisms behind SCC vs. form pressure

In literature, three papers dealing with predicting the form pressure by means of a physical approach are found; Vanhove et al. (2004), Ovarlez and Roussel (2006) and Graubner and Proske (2005). They all report on the use of the Janssen model, Janssen (1885) (as reported by all three papers) to predict the relation between vertical and horizontal stresses when using SCC in the same way as this model originally is used to describe granular materials’ lateral pressures on the wall of a silo cell. The Janssen model relates the horizontal pressure to the vertical pressure with the Janssen parameter, $K$:

$$p_{\text{horizontal}} = K \cdot p_{\text{vertical}}$$

In Vanhove et al. (2004), this physical approach was used to find the applicability of the Janssen model to two castings of SCC of walls 12 m high (1.784 m wide and 0.37 m thick). One wall was cast from the top and one was pumped from the bottom. According to the Janssen model, the authors’ state that the horizontal pressures are proportional to the vertical pressures where the constant of proportionality depends on the internal friction angle of the material. Further on, this model assumes that the friction stress (or the tangential stress) between the material follows the form of the Coulomb law and the friction constant is by the authors assumed to be constant. But contrary to granular material, concrete, which follows the Bingham model, has a yield stress and consequently this stress should be added to the friction stress. However, Vanhove et al. (2004) state that the yield stress of SCC is low and could be neglected. They further discuss that the theory by Janssen is based on the assumption that friction stresses are on the maximum limit, i.e., just below that leading to slip.

The friction coefficient measured by using the tribometer shown in Fig 3.40 indicated that the static value, valid for the pouring of SCC from the top since the pressure is evaluated at the end of the casting when the concrete has stopped, was approximately 0.06.

![Fig 3.40. Principle of the tribometer test, Vanhove et al. (2004).](image-url)
This value was not constant as stated by Coulomb, but varied within the actual pressure range between 0.05 and 0.07. The dynamic friction value, valid for the constantly flowing SCC pumped from the bottom, was approximately 0.02.

The model prediction, both with and without the correction coefficient $\alpha$, is compared to the actual measured and hydrostatic form pressures and shown in Fig 3.41. Using these friction coefficients they found that the model predicted pressures lower than the actual measured ones and to take care of these uncertainties, which they attribute to the friction, they introduce a correction coefficient, $\alpha$.

![Fig 3.41. Form pressures, measured and modelled, when pumping from bottom (left) and poured from the top (right). Curve (1) represents the hydrostatic pressure; curve (2) the measured stresses; curve (3) the modelled pressures without the coefficient $\alpha$ and curve (4) with the use of the coefficient $\alpha$. From Vanhove et al. (2004).](image)

It is worth noting that the model reported by Vanhove et al. (2004) does not at all include the structural behaviour of the SCC at rest while for the other papers dealing with this physical approach, Ovarlez and Roussel (2006) and Graubner and Proske (2005), this is a significant parameter to explain the development of lateral stresses (even if they treat this phenomenon with different approaches).

Ovarlez and Roussel (2006) use the Janssen model in a different way than Vanhove et al. (2004) in that the concrete is modelled as an elastic material confined in the formwork. They also use a Tresca plasticity criterion stating that the SCC yield stress, $\tau_0$, is the maximum stress sustainable by an internal plane.

They use the elastic theory with the boundary conditions that: (1) the stress at the walls is equal to $\tau_0$ and that (2) the walls are infinitely rigid. They also show that, in their approach, the Janssen parameter, $K$, is related to the Poisson ratio, $\nu_p$. If the material is incompressible, the Poisson ratio, $\nu_p = 0.5$ and consequently the Janssen parameter $K = 1$ (horizontal stress is equal to the vertical stress). But since SCC in general has a certain air content (normally around 2% without air entraining agent and approximately around 5% when air is deliberately entrained due to durability reasons), and therefore is compressible, the Janssen parameter can be lower than 1. The values of $K$ are by the authors computed using the Mori-Tanaka homogenization scheme (as referred to by the authors) and becomes equal to 0.931 if the air content is 5%.

The yield stress of the concrete at rest in the form is not constant but is found to increase linearly with time (which is also supported by the results reported by Billberg (2006)). Since the initial yield stress is small in relation to the increase with time it can be neglected and they introduce the expression of the time-dependent yield stress, $A_{\text{thix}}$ (Pa/s). They further show
that the lateral pressure at a certain depth, $H$ (m), is equal to a hydrostatic pressure reduced by the vertical stress at the walls which is between 0 and the concrete yield stress, $\tau_0$. They also assume that the vertical deformation due to the concrete’s own weight is enough to increase this shear stress to be equal to $\tau_0$. Considering that the casting rate, $R$ (m/h), is constant, $H = R \cdot t$, where $t$ is the time (h). By numerical simulation of the disturbed zone of the top layer of concrete during pouring it is found to be smaller than the thickness of the formwork, $e$ (m). Thus, at the bottom of the concrete resting zone, the resting time is $(H-e)/R$ and at the top equal to zero. Integrating the depth-dependant yield stress and incorporating the Janssen parameter and finally considering that the thickness ($e$ for walls or $r$ as the radius for columns) is neglected as it is much smaller than $H$, the ratio of lateral stress to the hydrostatic, $\sigma$, are calculated using the following expression:

$$\sigma = \frac{p_{\text{horizontal}}}{p_{\text{hydrostatic}}} = KH \left(1 - \frac{HA_{\text{thix}}}{peR} \right)$$

Ovarlez and Roussel (2006) use their model to compare computations with experimental results by Billberg (2003) and Khayat et al. (2005) and found that the value of $A_{\text{thix}}$ was around 0.6 (Pa/s) for the SCC used in Billberg (2003) and 0.2 (Pa/s) for the SCC used in Khayat et al. (2005). The results are shown in Fig 3.42.

The model described by Graubner and Proske (2005) assumes, just like Ovarlez and Roussel (2006), that the form pressure is influenced by the friction between the concrete and the wall and the time dependent behaviour of the concrete at rest. However, they relate this behaviour to the setting time and not to the development of yield stress.

By considering the Janssen model, and thus the Janssen parameter, $K$, as the ratio between horizontal and vertical stresses and the shear stress between the concrete and the wall (depending on the friction coefficient, $\mu$) they set up a differential equation for the horizontal
pressure which they solved using the Lagrange-method, see the details in Graubner and Proske (2005).

The time and load dependent values for the friction between concrete and wall and the Janssen parameter were measured simultaneously in a special devise, see Fig 3.43, where the vertical pressure, $p_{\text{vertical}}$ (denoted $F(v)$ in Fig 3.43), was increased with a hydraulic cylinder and the horizontal pressure, $p_{\text{horizontal}}$ (denoted $F(h)$ in Fig 3.43), was measured with load cells. Simultaneously an inserted steel blade was pulled out and the force, $F(r)$, was measured. Thus, the friction coefficient, $\mu$, and Janssen parameter $K$ could be calculated from these measurements.

![Fig 3.43. Devise for simultaneous measurement of the horizontal stress and the friction between concrete and, in this case, a metal blade. From Graubner and Proske (2005).](image)

Several mixes were tested having different water contents, aggregates, slump-flow values and setting times. The calculated results of $\mu$ and $K$ are shown in Fig 3.44 where they are plotted against a standardised time, i.e., the actual time relative to the setting time. Note that the Janssen parameter $K$ is denoted $\lambda$ in Fig 3.44.

![Fig 3.44. The time dependent values $\mu(t)$ and $K(t)$ ($= \lambda(t)$), from Graubner and Proske (2005).](image)
Graubner and Proske (2005) use these results of $\mu$ and $K$ to calculate the time-dependent pressure distribution over the height of the formwork.

### 3.7 Concluding remarks

Regarding the specific field of cementitious materials, this literature survey has shown that these materials are true thixotropic and also that the structural build-up is significant but not as rapid as the structural breakdown. Nevertheless, in the case of SCC, it is fast enough to reduce the form pressure depending on the time it is allowed to rest in the formwork, i.e., depending on the casting rate. Several methods to characterise thixotropy are treated in the survey and merely all of them have been used for cement paste and some also for concrete. It has also been shown that different components in the cement, e.g., the C$_3$A content, influence the degree of thixotropy. The same goes for particle fineness and concentration and of course also the surface active superplastizicers. In fact, all changes introduced to the concrete influencing the particle surfaces also influences the thixotropy. Recently the interest for thixotropy of SCC has grown considerably and several attempts to model the form pressure have been reported.
Chapter 4

Hypotheses

This project has been based on four major hypotheses which have influenced the planning and the execution of the laboratory studies. In the following these hypotheses are stated and discussed:

1. The origin of the true thixotropic properties of cement based materials is found in the colloidal interactions between particles in the fluid phase of concrete, i.e., the cement paste and thus, the larger aggregate particles can be regarded as totally inert.

For SCC, the continuous phase comprises, besides cement, water and the finest aggregate particles, also often additional powder materials, sometimes chemical viscosity enhancing agents (VEA) and/or air entraining agents (AEA) and of course a dispersing agent (superplasticizer). The different forces acting between these particles are discussed in Chapter 3 and the dominating ones are the attractive van der Waal forces and the repulsive electrical double layer forces. But since these forces are acting close to the boundary layer between the solid particle surface and the pore water, the superplasticizer molecules interact considerably with them and thus, influence the thixotropic structural build-up strongly.

2. The total structural build-up of SCC at rest is a function of a reversible, true thixotropic behaviour and an irreversible change of consistency over time, i.e., slump-loss.

Besides the reversible structural build-up discussed in the next paragraph, there is for SCC, like most concrete types, always an ongoing irreversible process causing a change of rheology with time. This process is complex and the mechanisms can be found in cement chemistry and the interaction (compatibility) between cement and, primarily, the superplasticizer. According to Ramachandran (1995), the mechanism involves both chemical and physical processes. Examples of the chemical processes can be the reaction of C₃A with gypsum or hydrate coatings restoring charge interactions between the C₃S grains increasing the flocculation. The physical approach is that cement particles coagulate during the dormant period.

3. The structure is represented by an elastic property of the fresh SCC and the maximum stress before the structure breaks characterises the magnitude of the structure.

The methodology of how to characterise the thixotropic properties is based on the aim to do this in-situ, i.e., to monitor the time-dependent structural build-up without breaking down the structure. Other, more traditional methods for thixotropical characterisation, such as those described in Section 3.3, are based on quantifying the structure by breaking down it. This is
done either by shearing the material at a constant level of shear rate and compare the initial and equilibrium stresses, respectively, or by performing a loop test where the area between the up and down curve represents the structure.

It is here assumed that SCC in general is a viscoelastic material, i.e., having both elastic and viscous properties. The rheology of a SCC kept in motion is dominated by viscous properties while left at rest the structural build-up transforms it into a more pronounced elastic material. Thus, the elastic part increases with time leading to that the SCC is transformed from a liquid to a more solid like material at rest. Therefore, the structure itself is here proposed to be represented by the elastic region of the fresh SCC and thus, the methodology is based on performing stress-strain measurements and characterise the magnitude of the structure equal to the peak stress (the static yield stress) where the material’s elastic structure breaks and turns the material into a plastic state. It is not possible to avoid the structure to break in order to quantify it, but the aim is to cancel the stress-strain sequence as soon as the peak level is reached and thus, before no significant structural breakdown occurs.

4. SCC is a material which builds up an internal structure at rest and this property influences the lateral form pressure.

Relative to the fresh properties of conventional concrete, fresh SCC can be said to have an extreme flowability. Using rheological terms, the material yield stress is low and sometimes approaches a Newtonian behaviour. If such a material is poured into a vertical form, the pressure will be equal to hydrostatic. But experience from many reported form pressure measurements (see Section 3.6.1) says that even though a SCC with a low degree of slump-loss is used, the pressure can be significantly lower than the corresponding hydrostatic pressure. The only relevant conclusion is that the SCC is building up a reversible, thixotropic, structure once it stops flowing and is left at rest.
Chapter 5

Thixotropy of the micro mortar phase of SCC

5.1 Introduction
This Chapter refers to the research and the results from thixotropy measurements on the micro mortar phase of SCC reported in Paper 1. The condition supporting the research significance of this project stage is that the study on the mechanisms is performed directly on the specific phase (micro mortar) of the concrete where they predominantly act. In Chapter 4 the fundamental hypotheses in this project are described. One of them deals with the basic mechanisms behind the thixotropical structural build-up of cementitious materials. These mechanisms are mainly to be found in the colloidal domain, i.e., generally speaking, among the particles having sub micron sizes. See also the discussions in Chapter 3. In this size-determined domain the dominating forces are the attractive van der Waal forces, the repulsive electrostatic double layer forces and of course also the dispersing mechanisms of the superplasticizer molecules. In addition, for these small particles also the Brownian motion is present working favourable for the forming of a structure at rest. These mechanisms are much less important for bigger particles for which instead such as gravitational forces, buoyancy viscous drag and particle inertia etc., dominate.

5.2 Rheology and mixing equipment

5.2.1 The rheometer Physica MCR 300
The rheometer used is a Physica MCR 300 which is a controlled stress (CS) rheometer; see Fig 5.1 where also the concentric cylinder sensor system, CC27P, is shown. The inner cylinder surface is profiled as shown in the upper right part of Fig 5.1. The purpose is to avoid any slippage to occur at this surface. The sensor system geometry is shown in Table 5.1.

Table 5.1. Geometry of the sensor system, CC27P.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner cylinder radius, $R_i$ [mm]</td>
<td>13.33</td>
</tr>
<tr>
<td>Inner cylinder height [mm]</td>
<td>40.00</td>
</tr>
<tr>
<td>Outer cylinder radius, $R_o$ [mm]</td>
<td>14.46</td>
</tr>
<tr>
<td>Gap [mm]</td>
<td>1.13</td>
</tr>
<tr>
<td>$R_o/R_i$ [-]</td>
<td>1.085</td>
</tr>
</tbody>
</table>
Fig 5.1. The Physica MCR 300 (left), the sensor system, CC27P, (top right) and the mounted inner cylinder (bottom right).

Discussing rheological measurements on particle suspensions, it is relatively important and thus, normally recommended that the gap between the inner and outer cylinders is approximately ten times the maximum particle size. It the actual case the gap is 1.13 mm and in order to meet the recommendation the aggregate tail included in the micro mortars is sieved so that the maximum particle size is 0.125 mm, i.e., less than a ninth of the gap size. However, some of the filler materials used have a few percent of the particles up to the size of 0.5 mm and this matter affects the rheology measurements slightly but only some single points are deviating from the hypothetically correct value and thus, this does not influence the measurements in practice as the representative example in Fig 5.2 show.

Fig 5.2. Up-curve of a rheology measurement showing an example of a slight disturbance when the coarser limestone filler, L1, is used compared to when the finer L2 is used.

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5.2.2 The Hobart mixer

For all the micro mortar tests, a Hobart food mixer shown in Fig 5.3 has been used. The mixing sequence, also shown in Section 3.3 of Paper 1, consists of the following steps: All dry materials are mixed for some 10 seconds at a low rotating speed using gear position 1. Now the water is added and the time is noted (the water adding time, WAT+) followed by adding the chemical admixtures. The micro mortar is then homogenized by hand using the whip shown in Fig 5.3 in order to disperse the admixture and make the mortar flowable enough to be mixed by the Hobart. This is done one minute at gear two, i.e., a higher speed and after this step again by hand one minute. The last two steps are repeated once again. Thus, the whole mixing sequence takes approximately five minutes to complete.

5.3 Preliminary tests

Initially in this stage of the project some preliminary tests were performed in order to search for a methodology that hypothetically would fulfil the aim discussed in Chapter 4, i.e., to monitor the structural build-up in-situ without destroying the structure in order to measure it.

First a series of tests were performed using the dynamic, oscillating technique described in Chapter 3 (Section 3.3). Even though some promising results were obtained (they will not be reported here), this approach was abandoned mainly due to the fact that the parameters resulting from this method, i.e., storage modulus, \( G' \) (Pa) and loss modulus, \( G'' \) (Pa) are somewhat difficult to relate to physical parameters resulting from other thixotropy methods. In addition, this methodology is not yet possible to repeat on the concrete scale. Thus, another approach, possible to perform also on concrete was searched for. The focus was now set on the specific ability for the used rheometer, the Physica MCR 300, to be stress controlled.

Five pure cement pastes with CemII/A-LL 42.5 R (Swedish cement for housing) at W/C ratios between 0.34 and 0.42 were tested using the configuration of the rheometer measuring sequence shown in Fig 5.4. The aim with this configuration is to measure the dynamic rheology before and after a resting period in order to find the magnitude of irreversible structural change with time. After the rest and before the last dynamic rheology measurement, the thixotropic structure is broken down with a relatively large shear rate loop. The linear regression according to the Bingham model is done on the shear rate interval 10 – 30 \( s^{-1} \) on each down-curve of the first and last loop, respectively. During the resting period, the time dependent static yield stress is measured. After successive resting periods of ten minutes, the paste is subjected to an increasing stress from 0 to 300 Pa at the rate 3.33 Pa/s until the structure breaks and the measurement is cancelled. The criterion for this cancellation is when the shear rate reaches 0.5 \( s^{-1} \), i.e., when the deformation due to the broken structure increases.
Chapter 5. Thixotropy of the micro mortar phase of SCC

Fig 5.4. Configuration of the rheometer for the preliminary tests on cement paste.

The results of each paste in this preliminary test series are shown in Fig 5.5.

Fig 5.5. The results of the dynamic yield stress development and structural build-up of the preliminary tests on cement paste with W/C ratios ranging from 0.34 to 0.42.
As shown in Fig 5.5, the time-dependent structural build-up at rest is very close to linear for all tested pastes (the worst correlation coefficient equals to 0.988 for the W/C = 0.42 paste). The dynamic and irreversible structural change over time ranges from 0.325 Pa/min for the W/C = 0.36 paste to 0.15 Pa/min for the pastes with highest W/C ratio. That equals to, respectively 19.5 down to 9 Pa/hour. The zero increase for the W/C = 0.34 paste is dubious. The time-dependent static yield stress ranges from 7.8 Pa/min for the densest paste (i.e., the lowest W/C) down to 2.5 for the leanest paste (highest W/C). The area between the static and dynamic curves in Fig 5.5 represents the reversible structure, i.e., the total structural build up minus the irreversible structure over time, and if plotted vs. the W/C ratio, we obtain the resulting correlation curve shown in Fig 5.6. Dealing with rheology, the W/C ratio is more related to particle concentration, i.e., the solid volume concentration (which sometimes also is referred to as the water to powder ratio, W/P). In this case, the W/C ratio is mostly regarded as a measure of interparticle distances in that a lower ratio represents smaller distances. Using this perspective, it is fully in line with the hypothesis stating that the narrower the particle system gets, the faster the structure is built-up. Note that the dubiously low dynamic rheology value of the W/C = 0.34 paste after the resting period makes the reversible structure for this paste somewhat overestimated.

![Fig 5.6. The correlation between W/C ratio and the reversible structural build-up for the tested cement pastes.](image)

**5.4 Methodology**

**5.4.1 Configuration of the Physica MCR 300**

It can be noted that the methodology in general worked well as described in Section 5.3, but in the case of the W/C = 0.34 paste, as indicated in Fig 5.5, the upper level of shear stress set to 300 Pa was reached as early as after 30 minutes of rest. It was also a wish to change the criterion for when to cancel the stress-strain measurement from the shear rate 0.5 s\(^{-1}\) down to 0.2 s\(^{-1}\) in order to decrease the disturbance of the structure after the peak stress is reached. The configuration of the dynamic rheology loops was also changed in that the down curve is easier to be interpreted if the shear rate is lowered stepwise down. Finally, a measurement after only 30 seconds of rest was added to the series of tests enabling the analyst to verify the absence (or not) of a structure so close to the dynamic rheology measurement. Thus, the final configuration as described in Paper 1 was chosen for this project stage.
5.4.2 Interpretation of the results

The most frequent way the results from this project stage are reported, as in Paper 1, is to plot the peak static yield stress value vs. time at rest (Fig 5.5) and to elaborate on the area between the dynamic and static yield stress curves (Fig 5.6), respectively. Another possibility is to relate the structural build-up to the slope coefficient of the linear response which is shown by the concrete in the project stages performed after this micro mortar stage. But there are also other ways possible to present the results, see Fig 5.7. In this example, Fig 5.7 (left), the configuration of the tests during the resting period is displayed in that the increase of stress reaches the level where the structure breaks and the shear rate suddenly increases. Each stress test is cancelled once the shear rate reaches 0.2 s\(^{-1}\).

The rheometer records a number of parameters during the tests and this enables plotting of many different graphs. In the example shown in Fig 5.7 (right) the same measurements as in Fig 5.7 (left) are plotted but here the stress against the strain and thus, the same kind of results as for the concrete stages are shown (see Papers 2 and 4). It is clear that also for the micro mortars, as for the concretes, the stress-strain behaviour displays a linear response until the structure starts to break and at higher strain values a plastic behaviour. Since the strain rate is not constant here, and because the measurements are cancelled rather quickly after the structure breaks, it is not possible to follow the decreasing stress at higher strain values.

![](image1)

**Fig 5.7.** Two examples of how to show the results of the structural build-up at rest; the shear rate – shear stress chart (left) and the stress-strain chart (right).

The time-dependent structural build-up of the micro mortars is not linear as in the case of the concretes but instead shows a more exponential shape; see Fig 5.8 where two representative examples are shown.

![](image2)

**Fig 5.8.** Exponential growth of the time-dependent static yield stress, \(\tau_s(t)\), for three micro mortars (left) and linear growth of \(\tau_s(t)\) for three concretes (right).
The explanation to this is possibly because the stress increase is slow enough (3.33 Pa/s) to enable the thixotropical structural build-up to progress simultaneously. As the internal structure grows with increasing time at rest, the longer time it will take to reach the peak stress value, i.e., the static yield stress at each measurement and thus, the longer time is available for the structure to grow. This is most probably the reason why the last (fifth) measurement results in a peak static yield stress far higher than what a linear regression on the first four measurements would predict.

5.5 Discussion of the outcome from this project stage

The methodology described in this Chapter has shown to be a both reliable and efficient (time saving relative to concrete tests) tool to investigate the mechanisms behind the thixotropic behaviour of cementitious materials.

By measuring the dynamic rheology before and after the resting period, it is possible to calculate the net structural build-up at rest, i.e. to separate the irreversible lost of consistency over time from the reversible, thixotropic structural built-up. This methodology shows that all tested micro mortars display significant thixotropic properties. Every single change of the basic mixes, e.g., varying the particle concentration, adding different types of powder materials, using different types of admixtures, influences the thixotropy.

There is a difference in structural build-up for the micro mortars with the two superplasticizer types, respectively. Since the electrostatic hindrance melamine SP shows a more pronounced ability to make the micro mortar building up a structure than the steric hindrance PCE SP it seems clear that the repelling forces for the PCE-polymers are longer in range relative to the repelling forces due to the electrostatic charge of the melamine polymers.

Rather surprisingly, the air entrainers (AEA) increase the structural build-up of the micro mortars during the rest period. This is relatively significant for both AEA types tested even though they are based on different active substances. No good hypothesis is at hand to explain this phenomenon. However, it is known that these admixtures influence the surface tension of the suspending media and this might possibly play a role in this thixotropy phenomenon.

The clay minerals increase the structural built-up during rest considerably due to their particles' ability of forming a three-dimensional structure at rest. Regardless if they have a flaky or a fibrous shape they form a structure of card-house type and intermeshed three-dimensional type, respectively. The reason for this is that the particles have different electric charges at the edge relative to the flat surface (in the case of flaky shape) or along the fibre length (in the case of fibrous shape) and thus, since edges attract to flat surfaces or to fibre long sides, the result becomes a three dimensional structure.

The mechanism of the structure of the viscosity modifying admixtures (VMA) is the result of extensive intermolecular association. This known mechanism of one of the VMA’s is through hydrogen bonding forming the structure. Even though the specific mechanism of the other VMA product is unknown, it is reasonable to assume some kind of similar mechanism also in this case.

By increasing the fineness of a powder material, i.e., increasing the specific surface, it results in that a larger part of the suspending media is adsorbed on the total particle surface. This also leads to smaller inter particle distances which hypothetically also promote the degree of
structural build-up. This is verified in this project stage when finer limestone filler replaces a coarser type.
Chapter 6

Structural build-up of SCC at rest

6.1 Introduction
This Chapter refers to Papers 2, 4 and 5 which all report from measurements of the structural build-up of SCC by using the ConTec 4 viscometer (Paper 5 is mainly discussed in the next Chapter but some results are taken from it to support the discussions here). The purpose of this Chapter is to discuss the methodology in more detail and to validate its reliability in terms of repeatability. However, the Chapter begins with discussing some results from an initial search for SCC with sufficient open time. Finally, the influence of the disturbance which the stress-strain measurement imposes on the SCC will be discussed, i.e., the dependence of if these tests are performed on the same sample during the whole resting time or on new and undisturbed samples each time.

6.2 Open time of civil engineering SCC’s
One of the most important requirements besides the three functional requirements; filling ability, passing ability and segregation resistance, is the one regarding open time. For obvious reasons, the SCC must have the appropriate fresh properties at the time of casting and thus, also if the transport takes up to one hour or so from the concrete plant to the construction site. It was also an important requirement in this project since the main interest here is to investigate the true thixotropic and reversible structural behaviour at rest and not on the irreversible part depending on slump loss. Note that the reason why this topic is brought up here is not to elaborate in detail on the exact mechanisms behind the very different open times caused by different constituents. Instead, the reason is to give some examples of different slump-loss behaviour just to support the discussions of how this influences the structural build-up and thus, also the development of form pressure (as mainly discussed in Paper 5).

In Fig 6.1 (left), the slump flow development approximately up to one hour after mixing for three SCC’s with different fine aggregates, respectively, are shown. Even though the initial slump-flow values for all of these mixes are 700 mm or higher, the slump-loss is significantly different. The mix design, representing a normal Swedish civil engineering SCC, is shown in Fig 6.1 (left) and information of the constituent materials used is found in Paper 5. It is worth noting that the three aggregate types are all originating from natural sources and thus, they do
not differ to any significant degree regarding porosity. The water absorption values are in the range of 0.5 to 0.7%. The only traceable difference is in the particle size distribution which is shown in Fig 6.1 (right). It might be interpreted that the relatively higher fineness of the Underås aggregate is the cause for the fast slump-loss, but since this aggregate is used in the tests on different admixture combinations shown in Fig 6.2 (left) it is obvious that it is possible to reach a good open time also with this aggregate. The small difference in particle size distribution between the aggregate from Sätertorp and from Vendels, respectively, results even though in a significant slump-loss difference. This phenomenon of slump-loss depending on fine aggregate characteristics is identified also by Esping (2004) and he addresses further research on this topic. The author agrees fully.

Fig 6.1. Slump flow development for SCC’s with different fine aggregates (left) and the particle size distribution for the aggregate used (right).

The slump loss for three SCC’s mixed with different admixture combinations is shown in Fig 6.2 (left). All the used superplasticizers are of Poly Carboxylate Ether type, i.e., belongs to the third generation of SP’s and the air entraining agents are, according to the deliverers, compatible with each SP, respectively. The EVO 26 plasticizer is delivered by Sika. It is clear that it is important to investigate suitable admixture combinations in order to achieve sufficient open time for the SCC.

Yet another parameter influencing the open time was discovered and that was the aggregate moisture in combination with mixer type (the mixers, Zyklos = 20 l batches and Eirich = 70 l batches, are shown in Section 6.3 in Fig 6.3). In Fig 6.2 (right) results are shown for a civil engineering SCC with the same mix design as the mixes in Fig 6.1 (left). Underås aggregate was used in this series.

Fig 6.2 Slump flow development for SCC’s with different combinations of superplasticizers and air entraining agents (left) and depending on aggregate moisture and mixer type (right).
The largest influence here is obviously the aggregate moisture which was either surface dry, i.e., a moisture content equal to approximately 0.2 % or with moisture content equal to approximately 3 %. The result in terms of open time is primarily in favour for the dry aggregate and secondarily for the smaller mixer type (dry aggregate).

In these entire tests, the same mixing sequence has been used even though also this has proven to influence the open time (not further discussed here but see the discussion in Paper 5 and Chapter 7 on how this parameter influences the results). The somewhat different results obtained with the Underås aggregate, i.e., working well in some series and worse in others were discovered to be due to individual batches of this aggregate delivered to the CBI laboratory. In addition, the cement batches delivered at different times over the years this project has been running has also influenced the fresh properties differently. Thus, we can conclude that factors influencing the irreversible structural change over time are many and in this investigation the following can be listed:

- different batches of the same aggregate type
- fine aggregate moisture
- admixture type and admixture combinations
- mixer type
- mixing sequence
- cement type
- different batches of the same cement type.

6.3 Mixers

Two different forced mixers have been used in this project. The smaller one, a Zyklos ZK 30 E, shown in Fig 6.3 (left) was mostly used in the project stage where the focus was set on the structural build-up of SCC. With this mixer, batches of 20 litres were mixed. The bigger mixer, an Eirich Intensive Mixer R 09 T shown in Fig 6.3 (right), was primarily used in the final stage where, besides the structural build-up also the form pressure was measured. With this mixer, batches of 70 litres were mixed.

![Fig 6.3. The two mixers used for concrete in this project; a Zyklos ZK 30 E (left) and an Eirich Intensive Mixer R 09 T (right).](image)
6.4 Equipment for stress-strain measurements

The methodology is quite thoroughly discussed in Paper 4 why merely some additional information regarding it and the equipment used for the stress-strain measurements will be given here.

6.4.1 The equipment setup

The whole setup of equipment is shown in Fig 6.4 where the ConTec 4 is located to the left with the concentric cylinder system mounted. To the right, the computer can be seen which normally is used to control the conventional dynamic rheology measurements. In the middle, the electrical panel stands with the door open to facilitate the access for the logger system terminal I/O connector to reach the unit where to collect the signals from the ConTec 4 load cell. In front of the electrical panel stands the computer with the data acquisition software.

Fig 6.4. View of the ConTec 4 and its open electrical panel with the computer attached to the SuperLogics equipment for data logging described also in Fig 6.5.

6.4.2 Logging of the signals

The signals from the ConTec 4 load cell are collected by a terminal I/O connector from SuperLogics, (model code UIO-37F-2), see Fig 6.5, via a cable (model code PCMP-C-D37-3) to a SuperLogics PC-card (model code PCM12H) in the computer.

The data signal acquisition software used is DASYLab basic version 7.0 which saves the logged values in ASCII format which can be imported into Microsoft Excel where the final data handling is done.

Fig 6.5. The hardware for logging of the signals from the ConTec 4 load cell.
Chapter 6. Structural build-up of SCC at rest

Just before the stress-strain measurement is initiated by pressing the “jog”-button on the ConTec 4 (a feature normally used to manually rotate the outer cylinder), a switch in the DASYLab panel is set to “on” and the signals are logged at a rate of 100 Hz. When the stress-strain measurement is terminated, the switch is set to “off” in order to reduce the amount of saved data.

6.5 Repeatability interpretation of the methodology

To be able to investigate the repeatability of the overall stress-strain methodology itself, it would be necessary to do that on a number of concrete mixes with the same mix design without any variations between different batches. This is however not possible in practice why these “normal” variations have to be accounted for when estimating the repeatability. Thus, two series in stage 3, i.e., series 1 and 4, of this project (reported in Paper 5) can be used for this purpose since the three SCC mixes in each series, respectively, have the same mix design. To make the discussion easier, some relevant information from Paper 5 is repeated here.

The structural build-up of mix H11-H13 (series 1, housing SCC) varies between 42 and 56 Pa/min while the same parameters for mix C21-C23 (series 4, civ. eng. SCC) are between 50 and 59 Pa/min. The curves from which these regressions are made are shown in Fig 6.6. If we for the sake of argument assume that the reversible thixotropic parts of the structural build-up are of the same order in each series, respectively, the variations might be found in the irreversible part.

![Fig 6.6. Structural build-up, $\dot{\tau}_s$ (Pa/min), for the SCC mixes in series 1 (left) and 4 (right) from Paper 5 (Fig 7 left and Fig 8 right).](image)

For the case of the civil engineering SCC’s in series 4, the difference in dynamic yield stress after mixing as well as the development over time is here regarded as negligible, see Table 6.1 and Fig 6.7 (right). Thus, the repeatability is here assumed possible to be estimated by the results of the structural build-up. The standard deviation for the results in this series equals to 4.6 Pa/min which represents 8.3 % of the mean value (55 Pa/min).

For the housing SCC’s the case is different. As can be seen in both Table 6.1 and Fig 6.7 (left) the rheology shows a higher dynamic yield stress for mix H12 after mixing and the development over time is on a higher level than for the other mixes in this series. This is also reflected by the difference in structural build up during the first 40 minutes at rest. After this time the curves for mix H12 and H13 bends somewhat downwards. Therefore a statistical
calculation is not found to be fully appropriate here. Visually however, incorporating the difference in dynamic yield stress development, the repeatability is in the same range for this series as for the civil engineering series.

Table 6.1. Rheology and fresh properties of SCC’s in series 1 and 4 from Paper 5.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Series 1</th>
<th></th>
<th></th>
<th>Series 4</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H11</td>
<td>H12</td>
<td>H13</td>
<td>C21</td>
<td>C22</td>
<td>C23</td>
</tr>
<tr>
<td>Slump-flow (mm)</td>
<td>680</td>
<td>670</td>
<td>700</td>
<td>715</td>
<td>685</td>
<td>690</td>
</tr>
<tr>
<td>Dynamic yield stress, $\tau_0$ (Pa)</td>
<td>67</td>
<td>87</td>
<td>57</td>
<td>8</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Plastic viscosity, $\mu_p$ (Pa·s)</td>
<td>43</td>
<td>60</td>
<td>52</td>
<td>105</td>
<td>104</td>
<td>103</td>
</tr>
<tr>
<td>Air content (%)</td>
<td>2.3</td>
<td>2.2</td>
<td>2.0</td>
<td>5.7</td>
<td>5.9</td>
<td>5.6</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2380</td>
<td>2390</td>
<td>2390</td>
<td>2350</td>
<td>2340</td>
<td>2350</td>
</tr>
</tbody>
</table>

Fig 6.7. Development of the dynamic yield stress, $\tau_0$ (Pa), with time for the SCC mixes in series 1 (left) and 4 (right) from Paper 5 (Fig 5 left and Fig 6 right).

6.6 Discussion on disturbed or undisturbed samples

In Paper 4, the significant influence of how the stress-strain measurements are performed on the resulting increase of the static yield stress with time at rest is discussed. This discussion will be continued here and for this, some of the results already reported in Paper 4 will appear here also.

From first sight, it can be reasonable to suspect that the method of performing consecutive stress-strain measurements on one sample that is slightly disturbed every time the peak stress is passed, underestimates the rate of static yield stress increase with time at rest. In order to investigate this, it was decided to mix a number of mixes and let them, respectively, rest differently long time before the stress-strain measurement and thus, be able to measure the level of static yield stress without any previous disturbance. To make this possible it was decided to mix four SCC’s and let the first one rest 20 minutes before the stress-strain measurement, the second one 30 minutes and the third 40 minutes. The fourth mix would then be tested as the original methodology and thus, would include the resting in 10 minutes before measured. Thus, this will give us a series of undisturbed samples tested at different resting time (10, 20, 30 and 40 minutes at rest) which could be compared to a “disturbed” series measured at the same resting time schedule.
Chapter 6. Structural build-up of SCC at rest

Such a setup of a test series would need to incorporate the aim to mix four SCC’s with as small variations as possible. As discussed earlier in this Chapter, the sensitivity of these SCC mixes is sometimes high and to try to validate the influence on the disturbance on mixes varying too much individually would be insecure. Thus, great care was taken to try to reach as high repeatability as possible between the four mixes and in Fig 6.8 (left) this is displayed in terms of slump-flow vs. dynamic yield stress. The variation, 770 ± 5 mm, in slump-flow values were sufficiently low for mix 2-4 but the value for mix 1 was only 740 mm and substantially lower and it is clear also how this is expressed in terms of dynamic yield stress. The dynamic yield stress values are mean values of two measurements and the max and min values for each mix is also indicated in Fig 6.8 (left). This might seem to be small variations even including mix 1 but in Fig 6.8 (right) it is clear how this affects the irreversible structural change with time (i.e., the slump-loss). The three mixes Nos. 2-4 have more or less the same development while mix 1 has a much steeper increase.

![Image](image1.png)

**Fig 6.8.** Relation between slump-flow and dynamic yield stress for mix 1-4 (left) and the time dependent increase of the dynamic yield stress for mix 1-4 (right).

The results from the measurements on disturbed and undisturbed samples are shown in Fig 6.9.

![Image](image2.png)

**Fig 6.9.** The increase of static yield stress with time for the disturbed mix 4 compared to the undisturbed mixes 1-3. Note the indicated hypothetical location of the peak static yield stress for mix 1.
Quite contrary to the first assumption that the disturbance would lead to an underestimation of the structural build-up it seems from these results that it instead is overestimated. Since the results of mix 2-4 show a nearly perfect linearity, regardless of disturbances or not, it might be correct to assume that the deviating value for mix 1 at 40 minutes at rest is affected by the fact that this mix has a much faster rate of slump-loss than the others. This is indicated by the hypothetical shifting of location for the peak stress value for mix 1 in Fig 6.9.

The mechanism behind this rather surprising result is not known at the time of writing this thesis but according to Roussel (2006b), the same kind of surprising behaviour has been recognised also by this research group, i.e., that cementitious materials do show a strain-hardening behaviour if resting under the influence of shear stress but not if resting under no shear stress. This means that, apparently, the flocculation rate is favourably influenced by the increasing stress itself during the stress-strain measurements, at least in this project. This strain hardening behaviour is also reported by Min et al. (1994). They report on measurements where cement paste was subjected to squeeze flow and showed an elastic response at low strain levels, plastic response at intermediate strain levels and a strain hardening response at high strain levels.

Roussel (2006b) refers to test (not yet published unfortunately) where cement paste was enabled to rest under no influence of shear and when the start of flow was studied at an inclined plane it began at the wall interface. If however, the paste was subjected to a shear stress during resting, the flow started a distance from the wall when the plane was inclined. Thus, the paste of a certain thickness closest to the wall was apparently more flocculated due to the shear stressed rest.

The question arises of whether the disturbed structural build-up after all is more representative as to the concrete resting in a formwork. In Chapter 3, Section 3.6.3, three physical approaches for models to predict the form pressure when using SCC is presented. The theory reported by Ovarlez and Roussel (2006) discusses the Janssen model by modelling the SCC as an elastic material confined in the formwork. They state that one boundary condition is that the shear stress at the walls is equal to $\tau_0$ (not higher since that would mean that the concrete yields) and that this is possible since SCC normally can be regarded as a compressible material due to the air content. This way of arguing leads to the conclusion that when the concrete compresses due to the load of concrete layers above the actual shear stress at the walls reaches the yield stress, $\tau_0$, and thus, the concrete is subjected to a shear stress during rest.

Still, this is just a hypothetical discussion and the answer to the mechanisms causing this strain-hardening behaviour is not at hand yet. Roussel (2006b) refers to a French project just started aiming at understanding this specific phenomenon and the answer might be obtained within this project.

6.7 Discussion of the outcome from this project stage

The results from this stage of the project where the structural build-up of SCC is measured with stress-strain technique using a ConTec 4 viscometer are interesting from a number of reasons.
First of all it is here clarified that all tested SCC mixes are thixotropic and builds up an internal structure at rest and that this structural change is caused by both an irreversible and a reversible part. The irreversible part is normally referred to as slump-loss while the reversible part is the true thixotropic behaviour.

Secondly it can be stated that the overall methodology enables a separation of these two parameters summing up to the total structural build-up at rest.

The structural build-up is close to perfectly linear which makes it possible to be predicted after only two or maybe three consecutive measurements during the resting time.

By analysing the stress-strain results in detail it is evident that when SCC, after a time at rest, has developed an internal structure it displays an elastic behaviour at stresses below the static yield stress. Thus, the magnitude of the structure within the concrete can be related to this elastic response.

The methodology can be used to distinguish between different mixes having different particle concentrations, different superplasticizers, and different particle fineness.

Finally, it has been shown that there is a significant difference of the structural build-up of SCC at rest depending on if the resting is stress-free or if the SCC is subjected to stress during the rest. The methodology displays that the tested SCC’s show a strain-hardening behaviour, i.e., flocculates faster if subjected to a shear stress during rest. It has been discussed, due to lack of evidence a pure hypothetical discussion, on whether the case for the concrete in a formwork is a stress-free rest or not.
Chapter 7

Structural behaviour of SCC vs. form pressure

7.1 Introduction
This Chapter refers primarily to the methodology of form pressure measurements using the monitored steel tube, to some of the results of the final laboratory stage in this project reported in Paper 5 and the outcome of this project stage. Thus, the purpose of this Chapter is mainly to complete the description of the methodology and equipment in Paper 5 and to elaborate on the reliability, precision and outcome of the results. All details regarding materials and mix designs are to be found in Paper 5 and thus, not shown in this Chapter.

7.2 Methodology

7.2.1 The pressure tube
The original idea of using a monitored tube with an ability to simulate higher casting heights and rates was discussed in 2003 during a reference group meeting in this project. Subsequently, it was further discussed during a planning of a mutual research between the author and the University of Sherbrooke, Quebec, Canada. Even though this research was cancelled, the first tube made was manufactured by Joseph Assaad, of U of S, who described his tube in his doctoral thesis, Assaad (2004). However, no result using the Canadian tube has been reported yet.

The principle design of the stainless steel tube used in this project is shown in Fig 7.1 (some photos of the tube are shown in Paper 5 together with some additional details). Each end of the tube is sealed with bolted plates and rubber gaskets. An air inlet with a pressure regulator, an outlet valve and a manometer are mounted on the top plate.

As indicated in Fig 7.1, the upper level of concrete is

Fig 7.1. Sketch of the pressure tube with measures in mm.
limited to just below the upper pressure cell (cell +1050) in order to enable this cell to register the exact overpressure. From the beginning the aim was to use all these five cells for monitoring the concrete pressure but it was discovered a difficulty to keep the pressure exactly constant due to limitations of the pressure regulator and thus, the cell +1050 was sacrificed to measure the air overpressure instead.

Before each measurement, the inside of the tube is greased with a vegetable type of form releasing agent in order to ease the emptying of concrete from the tube, sometimes up to 4 hours after casting. Care is taken to avoid any excess amount of the form releasing agent on the inner tube surface.

7.2.2 The pressure cells

The pressure cell shown in Fig 7.2 is a Honeywell ABH100PSC1B with a pressure range of 0-689 kPa (0-100 psi). The cells have to be supplied with an input voltage of ±5 (max 6) V and when the cell membrane is subjected to a pressure difference the output signal is in the 0 ± 100 mV range.

The cells are mounted with washers, rubber gaskets and three screws per cell to sockets which are welded to the tube wall, see Fig 7.2. Each of the five cells is located with an equidistance of 250 mm in between each other, beginning 50 mm from the bottom of the tube, see Fig 7.1. When mounted, the cell membranes become flush with the inside of the tube.

7.2.3 Logging of the signals

The signals from the pressure cells are collected and treated using the same hard and software as described in Section 6.3.2. The only difference in data logging is that the signals from the pressure cells are constantly logged at the 100 Hz rate but the data saved are thinned out to be equal to 1 Hz, i.e., 1 value each second.

7.2.4 Calibration of the pressure cells

When the end plates and the cells are mounted and the air overpressure hose is attached the calibration is done. First the mV values of each cell representing the zero overpressure is logged at 100 Hz approximately 2 seconds. Then the air overpressure is increased to 300 kPa according to the manometer and again the signals are recorded during approximately 2 seconds. These pairs of mV values for each cell at 0 and 300 kPa pressures, respectively, are now saved in the DASYLab software and thus, used as calibration constants with a linear relationship between these pressure levels. The QA of this calibration is further discussed in Section 7.4.
7.3 Pressure measurements

7.3.1 Casting of the tube

The casting of the tube is done with three buckets of SCC and the characteristic pressure response in each cell is displayed in Fig 7.3 where the measurement is taken from the testing of mix C21. Note the disruption of the pressure increase when pouring the third bucket. This is due to a careful adjusting of the SCC upper level which should be as high as possible but still below the upper cell +1050. In all, the filling takes slightly more than one minute and when completed, the upper sealing plate is mounted and the air inlet pressure hose attached.

![Fig 7.3. The principle appearance of the increasing pressure at each cell during casting of the tube with three buckets of SCC (mix C21).](image)

7.3.2 Form pressure directly after casting

As indicated in Fig 7.3, the difference between pressure responses at each height level (each cell) is fairly constant and since the distance between the cells is constant, the pressure slope is close to linear. This fact is verified by plotting the measured pressure slopes as shown in Fig 7.4 which represents the examples taken from testing of mixes C21-C23 (series 4 in Paper 5).

![Fig 7.4. Example of pressure slopes directly after finished casting taken from series 4 reported in Paper 5. Regressions show perfectly linear (hydrostatic) pressure slopes.](image)
Note that all regressions show that the pressure slopes in each case is perfectly linear and equal to a hydrostatic pressure. This example of appearance is representative for all mixes tested even though only the result of this actual series is shown here.

### 7.4 Calibration and reliability of the pressure cells

The reliability, meaning the precision and repeatability of form pressure measurements in the tube, i.e., development of pressures with time, is difficult to quantify. The reason is that it is almost impossible to mix a number of SCC’s having exactly the same initial rheology and the same development of reversible and irreversible structure over time even though they have exactly the same constituents and the same individual proportions.

Instead, the pressures measured directly after finished castings can be used to evaluate the reliability of the pressure cells, i.e., the accuracy of calibration and the ability of the cells to correctly measure the pressure from the concrete. By using the measured densities of the fresh SCC’s in series 4 (mix C21-C23 having the same mix design) and the respectively casting height in the tube, the hydrostatic pressure can be calculated and compared to the maximum pressures predicted by the regressions shown in Fig 7.4. These values are shown in Table 7.1.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Density [kg/m³]</th>
<th>Air cont. [%]</th>
<th>Height [mm]</th>
<th>Max. calc. p [kPa]</th>
<th>Max p regr. [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C21</td>
<td>2351</td>
<td>5.7</td>
<td>1045</td>
<td>24.1</td>
<td>24.4</td>
</tr>
<tr>
<td>C22</td>
<td>2344</td>
<td>5.9</td>
<td>1045</td>
<td>24.0</td>
<td>24.6</td>
</tr>
<tr>
<td>C23</td>
<td>2347</td>
<td>5.6</td>
<td>1040</td>
<td>23.9</td>
<td>24.1</td>
</tr>
</tbody>
</table>

For these mixes it is relevant to assume that the correct hydrostatic pressure only depends on the concrete height since the air content and, i.e., also the densities vary very little, see Table 7.1. The calculated values of maximum pressures at the bottom of the tube are for all mixes $24.0 \pm 0.1$ kPa while the pressures according to the regressions are slightly higher; $24.35 \pm 0.25$ kPa. Thus, considering that the densities are correctly measured, the maximum error equal to 0.6 kPa is here the one for mix C22 and it represents an overestimation of the correct pressure by 2.4 %.

The overall precision of the methodology of pressure measurements in the tube, i.e., including variations of concrete properties are discussed in Paper 5. In respectively test series No. 1 and No. 4 the same mix designs is used and only the casting rate is varied. In theory this would lead to the same development of form pressure but in reality some deviations were found. However, the major part of the deviations between the measurements within each series in terms of form pressure can be explained by differences in initial flowability (i.e., rheology), structural build-up and slump-loss, see further the discussion in Paper 5. Thus, it is the author’s opinion that the precision of this methodology is satisfactory.
7.5 Limitations due to concrete stiffness

It has been discovered in some of the tests that when the SCC in the tube gets sufficiently stiff the over pressured air above the upper concrete surface slips in between the concrete and the tube wall. An example of this phenomenon is displayed in Fig 7.5 where the pressure of cell +800 only approximately one minute after the increased overpressure suddenly increases to the level of the overpressure. A few minutes later the pressure of cell +550 increases to the same level followed later on by also the lower cells +300 and +50 to this overpressure level. The only relevant conclusion is that the over pressured air gets in between the concrete and the tube wall and affects the cells below the upper level of the concrete. Note the pressure response of the cells due to the small intervals of increased overpressure (at WAT + 245 and 248 minutes, respectively).

Most probably two phenomena act together to make this happen; (i) the overpressure increases the tube diameter and (ii) when the concrete gets stiff enough it contracts (shrinks).

In Fig 7.6 a sketch of a horizontal section of the tube with radius \( r \) and wall thickness \( t \) and the forces \( F \) acting on the tube wall due to the overpressure \( p \) are shown.

The equilibrium state of an infinite sector of the tube with the sector angle \( 2 \cdot d\phi \), as shown in Fig 7.6 (right), results in the equation:
$2F \cdot \sin \phi = P \cdot r \cdot 2 \cdot d\phi$, but for small angles $\sin \phi \approx \phi$ and thus, $F = P \cdot r$. Per unit height, the tensile stress is $\sigma = \frac{F}{t} = \frac{P \cdot r}{t}$ and thus, the strain is $\varepsilon = \frac{P \cdot r}{E \cdot t}$ and the expression for the increased radius, $\Delta r$, when the wall circumference increases due to the overpressure becomes: $\Delta r = \varepsilon \cdot r = \frac{P \cdot r^2}{E \cdot t}$.

This means that for an overpressure of $75$ kPa (as in the actual case), an elastic modulus of the steel equal to $200$ GPa and the actual geometry according to Fig 7.6, the radius increases with $1.25$ micrometer. This value is probably an overestimated and pure theoretical value since the tube is sealed at each end which effectively stiffens the tube and thus, limits this elastic increase of the diameter at the level of concrete free surface.

Even though the increased radius of the tube due to overpressure is small it might be the answer to this phenomenon since it works together with the second hypothesis, i.e., that the concrete itself shrinks during the time where the structural change is working or at least when the duration of the test is as long as $4$ hours. In any case, since this limitation of the methodology occurs only when the irreversible structural change has developed very far after several hours and at this time it does not affect the primary scope of this work, i.e., to study the thixotropic structural build-up and its influence on form pressure. This discussion is visualised in Fig 7.7 showing the degree of stiff consistency of the SCC after $4$ hours.

![Fig 7.7. A stiff SCC after emptying the tube, at 4 hours of age.](image)

### 7.6 Discussion on active and passive pressure

The methodology described in Chapter 6 and Paper 2 and 4 shows that the elastic strain response of fresh SCC increases with time and that this property relates to the structural build-up. When discussing the influence of this property on the behaviour in the form, i.e., the concrete’s ability to withstand vertical load without increasing the horizontal pressure to the same degree, the question of the form properties itself arises. The tube used in this project is relatively stiff which the example of calculated increase of the radius due to overpressure in the last Section shows. Thus, the question is how this influences the development of the form pressures. A way to find out this is to see whether the rate of increasing overpressure...
influences this development. Fig 7.8 is taken from Paper 5 (the part showing the first 100 minutes of Fig 9 left) and shows how the pressure at cell +50 relative to the overpressure for mix H11-H13 decreases with time. For these mixes, having the same mix design, the pressure is increased in steps of 18.8 kPa with different rates, respectively. The pressure for mix H11 is increased three times during the first 100 minutes while for mix H13 and H12 one and two times, respectively. The small variation of results between the different mixes shown in Fig 7.8 indicates that the degree of pressure decrease is not (at least primarily) influenced by the increasing overpressure. Thus, it can be concluded that the primary mechanism behind the pressure drop is the structural build-up of the SCC’s leading to a contraction large enough to release the horizontal pressure against the tube wall.

Fig 7.8. Pressure development for mix H11-H13 up until 100 minutes after finished casting. Detail of Fig. 9 (left) from Paper 5.

7.7 Comments on the methodology
This Chapter has discussed the methodology of using the monitored steel tube to investigate the form pressure development with time. It has been shown that the tube is sufficiently reliable to be used for this purpose because of the following reasons: (i) it can be verified that the calibration is sufficiently precise and that the pressure cells used are suitable for measuring the pressure of the concrete, (ii) the limitations of the methodology due to stiff concrete does not affect the primary scope of this project, i.e., to focus on the structural behaviour and form pressure up until the SCC’s gets stiff (during the first hours) and finally (iii) the measurements are not significantly influenced by the properties of the tube in terms of stiffness but instead primarily due to the structural behaviour of the tested SCC mixes.

The repeatability, which has to be judged in the light of normal, and unavoidable, variations between different mixes having the exactly same mix design, can also be regarded as good. This is shown by the results of Series 1 and 4 (see Paper 5).

With the favourable possibilities to control the overpressure above the upper concrete level, high structures (up to approximately 28 m high) can be simulated and in addition the casting rate can be varied. This makes the tube an efficient tool to be used in a laboratory environment for form pressure measurements.
7.8 Discussion on the outcome from this project stage

Several interesting results are obtained in this last project stage. Here, the relationship between dynamic yield stress and structural build-up, influence of small variations and the relationship between structural build-up and form pressure will be discussed.

Focusing on the tested SCC mixes, one of the most important results is the surprisingly large influence of the choice of cement type, the finest tail of the aggregate and mixing sequence on the structural build-up and form pressure development. The measurements show that these factors can influence the irreversible structural change, i.e., the slump loss to such a degree that the reversible thixotropy becomes relatively insignificant. Thus, the influence of the dynamic yield stress development on the structural build-up is clear.

The results also show that very small variations, for instance in terms of slump-flow value after mixing have a relatively large influence on the irreversible slump-loss and in turn substantially affect the structural build-up and form pressure development. This was caused by small variations of superplasticizer doses which in reality can be difficult to avoid.

An overall view of the tested mixes shows that, apparently, there exists a threshold value in terms of structural build-up (Pa/minute) before the form pressure reduces significantly with time. Fig 7.9 is taken from Paper 5 and shows that this threshold is, at least, above approximately a value of 80 Pa/minute. This correlation between structural build-up and form pressure decay with time can be used to predict how a certain SCC mix will affect the form pressure in practise.

![Fig 7.9. Influence of structural build-up on the reduction of the form pressure, from Paper 5.](image)

Finally, it is interesting to conclude that regardless of the reasons behind the concrete variations, the methodology is able to measure the influence they have on the dynamic yield stress development (slump loss), on the structural build-up (reversible + irreversible structure) and finally on the form pressure development.
Chapter 8

Conclusions and recommendations

8.1 Conclusions

The laboratory tests in this project have basically been performed in the following three stages; structural build-up of SCC micro mortar phase (discussed in Chapter 5 and reported in Paper No. 1), structural build-up of SCC (discussed in Chapter 6 and reported in Paper No. 2 and 4) and finally, the influence of the structural build-up on form pressure (discussed in Chapter 7 and reported in Paper No. 5). Besides these stages also a literature survey is carried out which is reported in Chapter 3 together with some concluding remarks (Section 3.7) and therefore not repeated here.

Bearing in mind the obvious limitations of the range of the conclusions, i.e., not necessarily going beyond the tested mixes and in-going variables used in the laboratory tests, the following conclusions regarding material characteristics and methodologies, split between the stages, can be drawn:

8.1.1 Structural build-up of SCC micro mortar phase

- The results show that decreasing interparticle distances increase the time-dependent growth of the internal structure. These interparticle distances decrease if the solid concentration and the particle fineness increase. Also the influence of superplasticizers is verified in that the increasing dose decreases the structural build-up. The methodology could even differ between the dispersing mechanisms of the different superplasticizer types. The older melamine type having a dispersing mechanism dominated by electrostatic hindrance increased the structural build-up more than the newer PCE type with a pronounced steric hindrance mechanism. This can be explained by considering the difference in repelling force range which is longer for the steric hindrance dispersing action. The increased thixotropy introduced by the clay mineral and the viscosity entraining agents also verifies the hypothesis behind their action mechanism. For the clay mineral this mechanism is to build card-house like structures at rest and for the viscosity agents, their large molecules get entangled at rest and thus, increase the structure. However, this is when the superplasticizer dose is kept constant (see further the discussion in the next Section).

- The developed methodology for the structural build-up using the ability for the rheometer to be stress-controlled can detect the increased time-dependent structure and separate the irreversible and reversible structural change over time, respectively. The methodology also shows to be very sensitive, making it possible to study the influence of even small changes of any parameters.
- The time-dependent structural build-up of the micro mortars is not linear as in the case of the concretes but instead shows a more exponential shape. The explanation to this is possibly because the stress increase is slow enough (3.33 Pa/s) to enable the thixotropical structural build-up to progress simultaneously. As the internal structure grows with increasing time at rest, the longer time it will take to reach the peak stress value, i.e., the static yield stress at each measurement and thus, the longer time is available for the structure to grow.

- The results obtained in this project stage confirm hypothesis No. 1 discussed in Chapter 4, i.e., that the origin of the thixotropic properties of cement based materials is found in the colloidal domain, i.e., in the fluid phase of concrete. Of course one can argue that no systematic study has been performed within the scope of this project on how the coarser aggregate fractions influence the thixotropy. However, besides the lack of logics regarding such a hypothesis (authors comment) no information can be found in literature discussing such a hypothesis but instead a statement that the thixotropy is dependant on the “second attraction minima” referring to the van der Waal attractive forces, Barnes (1997).

8.1.2 Structural build-up of SCC

- It has been shown that all tested SCC’s have, even though to a broad degree of variation, thixotropic properties in the fresh state. The same trend as for the micro mortars is shown and thus, the verification of the hypothesis (No. 1) goes also for the concrete phase. However, relating to the micro mortar results where in most series the superplasticizer (SP) dose was kept constant, the aim when mixing SCC was instead to reach the target value around 700 mm in terms of slump-flow. Therefore the superplasticizer dose had generally to be adjusted from mix to mix. This means that the addition of, e.g., clay minerals, finer fillers and VMA’s increased the SP-demand and this resulted in a decreasing structural build-up. Thus, apparently the influence of the dispersing mechanism of the used SP’s dominates over the thixotropic mechanism of the additives. This can be considered a general conclusion.

- The results show that the overall structural build-up at rest is influenced by two different parameters; (i) the irreversible structural change over time, normally referred to as the slump-loss, and (ii) the reversible change over time, i.e., the true thixotropic behaviour. This confirms hypothesis No. 2 discussed in Chapter 4. The development of these two parameters cannot individually be predicted by just measuring the slump-flow or rheology during the time between mixing and the casting process. Instead, how a SCC will behave at rest in the formwork is a question of measuring the overall structural build-up, which the method developed in this project offers.

- The results of the stress-strain measurements follow the characteristic behaviour shown in Fig 8.1 of an elastic material ① up to a critical stress where the structure breaks ② (the critical yield stress) and thereafter keeps breaking down showing a more and more plastic behaviour as the strain increases ③. If the constant strain rate is prolonged enough, the stresses decrease to an equilibrium level ④ representative to the actual used strain rate.
- The increasing growth of the static yield stress is linear which makes it possible to predict the behaviour up to one hour by performing only two consecutive measurements (e.g. after ten and twenty minutes, respectively). The increasing stress during the measurements is faster than for the micro mortar and thus, the thixotropical build-up during the actual stress-strain measurement can be neglected. Thus, the characteristic result shown in Fig 8.1 together with the increasing growth of the static yield stress with time (also shown in the micro mortar stage) confirm hypothesis No. 3, discussed in Chapter 4, stating that the structure is represented by an elastic property of the SCC and the maximum stress reached when the structure breaks characterises the magnitude of the structure.

- The structural build-up is significantly influenced by the way it is measured. If the stress-strain measurement is performed on the same sample which is thus disturbed every ten minutes, a significantly higher degree of structure builds up with time than if the same measurements are carried out on undisturbed, individual, samples at each time at rest. The possible explanation is the one discussed in Chapter 6 regarding the strain hardening behaviour of fresh suspensions of cementitious materials. This phenomenon has been identified also by others, Roussel (2006) and Min et al. (1994).

- The open time (or slump-loss) of the SCC is extremely important for the development of the structural build-up. In other words, a SCC with an open time corresponding to approximately constant rheology for one hour after mixing builds up a considerably lower structure than a mix with severe slump loss. In addition, the influence of constituents, i.e., cement, aggregate and superplasticizer and the mixing sequence on the open time is surprisingly large. This fact, that so many parameters influence the open time makes the prediction of how a mix will behave at rest very insecure and thus, its behaviour must be verified using the developed methodology able to measure the net influence of thixotropy and slump-loss.

### 8.1.3 Simultaneous measurement of structural build-up and form pressure

- The monitored tube is an excellent tool to use in a laboratory to investigate the form pressure. By increasing the overpressure, higher structures can be simulated and by controlling the rate of pressure increase, the simulated casting rate can be varied.

- However, even though not affecting the usability in practise, one limitation of this methodology can be identified. Even though the tube is relatively stiff, the over pressure can increase the tube diameter and this together with concrete stiffness exceeding a certain value.
enable the air to get in between the concrete and the tube and thus, the recorded pressure by the pressure cells now equals the air overpressure and not concrete pressure. The experience from this project is that this phenomenon occurs only when the concrete gets significantly stiff after several hours. This is only of secondary importance since at this late stage the interest of the form pressure is of lower degree.

- The correlation between structural build-up and form pressure verifies the hypothesis No. 4, discussed in Chapter 4, stating that the structural build-up influences the form pressure. The results show that the structural build-up must be in the range of 150-200 Pa/min to reduce the form pressure to any significant degree. Below 80 Pa/min the reduction of form pressure during the first hour is so low that it can be regarded as insignificant.

- Small variations in constituents such as aggregate and cement (between delivery batches and not only between types) and also the mixing sequence have shown to influence the SCC fresh properties to such a degree that both the structural build-up and form pressure are significantly affected.

- The methodology developed in this project is able to measure the influence of any small material variation in terms of dynamic yield stress development (slump loss), in terms of structural build-up (reversible + irreversible structure) and finally in terms of form pressure development.

- Development of more variation-free (robust) SCC mixes, in future, is a must in order to secure an adequate prediction of the form pressure. Today even small variations in the constituent materials properties result in large rheological variations and thus, also in the development of form pressure.

### 8.2 Recommendations

This project has increased the understanding of how normal Swedish SCC mixes, both for housing and civil engineering purposes, act during the first hours regarding thixotropy and slump-loss, i.e., the overall behaviour at rest and how these parameters influence the form pressure. The measurements have, however, been performed in a laboratory environment and it must be kept in mind that many parameters outside the scope of this project are known to influence the pressure to a significant degree. As the proposals for future research is described in the next Chapter 9, the material properties investigated in this project must be incorporated in a more comprehensive model for form pressure calculations where the influence of several other parameters is studied.

The mapping of the material properties has started in this project and tools for further research regarding SCC mix design and additives have been developed. However, the full picture is not at hand yet and to complete it more research is needed. As a consequence, it must be recommended here that in the nearest future the question of how to design formwork systems for SCC still has to be treated conservatively. If experience exists on how a certain SCC mix, planned to be used for casting, influences the form pressure, of course, this knowledge should be used for a refined formwork design. But if a new concept is to be used (i.e., a new mix design, a new casting method, at a different temperature etc.) either a hydrostatic pressure has to be the basis for the design loads, or the material properties, under the actual circumstances, have to be mapped using the methodology developed in this project. Another possible concept, where the material properties will play a minor role, is to develop a formwork concept where the form pressure is measured on-line in real time. With such a system, the
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casting process can be controlled to keep the pressure on the safe side regarding formwork deformation or collapse.

Some recommendations based on the results of this project can, however, be mentioned here. Housing SCC, as designed in this project with relatively high W/C ratio (0.58) cannot be regarded as sufficiently thixotropic as to reduce the pressure below hydrostatic. This goes at least for normal castings of storey high walls where it usually is far more economic to cast quickly and strengthen the formwork to resist the high pressure. Civil engineering SCC can build up such a strong structure that the pressure is reduced far below hydrostatic, but this is at the cost of slump-loss. The civil engineering SCC’s with long open time showed no more structural build-up than the housing mixes and, therefore, unless the form is designed for high pressures, great care should be taken using such a mix at high or possibly even at moderate casting rates.

Finally, it cannot here be stressed enough powerfully that at the present situation, where the fresh properties of SCC vary to such a considerable degree due to high sensitivity, a safe prediction of how formwork pressure will develop for a casting including several delivered batches is not at hand. For the concept of SCC as a whole, further research on how to create variation-free SCC is nothing less than a must.
Further research in several areas is necessary in order to enable the concept of SCC to be utilized to such a degree as it has potential for. In Section 9.1, some general research areas are suggested while Section 9.2 is focusing on areas identified in this project.

9.1 General aspects to be focused on

Basically, the question (problem) of SCC scatter in fresh properties at deliverance to the site is currently the most essential aspect to focus on since all other aspects rely on this fact. For example, if the form pressure should ever be able to be predicted reliably, the precision regarding the fresh properties must be increased from the situation today. As discussed in Chapter 8, one conclusion of this project is that there is a difference in the time-dependent behaviour of a SCC mix solely due to a slight variation of, e.g., the superplasticizer dose which in turn, in reality during production, could be caused by misjudged aggregate moisture or a deviation in weighted powder amount. This sensitivity is not only the experience from laboratory test but also from full-scale production of SCC.

Once (or when, or in the worst case: if) the mechanisms behind the variation of SCC fresh properties are identified (research at CBI is initiated) and thus, the tools to enable a variation free production is at hand, the real possibility for an adaptation to the full extent of this technique arises. This implies, e.g., a reliable prediction of form pressure (i.e., the thixotropic behaviour), simulation of fresh SCC flow and the casting process (on-going research at CBI, Gram (2006), and elsewhere) and of course for the possibility to transform the whole construction process to fully utilise the substantial profits possible by using SCC. Such knowledge will also open up the field of developing new chemical admixtures, other types of constituent materials and production systems for specific applications.

The construction process comprises also the formwork systems. One important change is to take advantage of the fact that casting using SCC is merely to pour a liquid into any formwork. It may have any possible architectural geometry and stay in place or not. SCC may be poured from the top or from below and thus, enabling a more industrialised casting process. Another change concerns how to deal with the form pressure issue. If a prediction of the structural build-up and the form pressure is found to be too insecure (as discussed in Chapter 8), the way to go could instead be to perform on-line measurements of the real-time pressure during casting. The formwork can either be permanently equipped with pressure
cells, strain gauges or equal to control the casting rate relative to the actual SCC behaviour at rest. If not permanently installed, a system for on-line measurements of the lateral pressure could be developed to be customized for any possible application.

9.2 Material properties

This doctoral project has mainly dealt with material properties of SCC and its fluid phase, i.e., the micro mortar phase and laboratory studies of the form pressure and therefore many parameters influencing the form pressure are left out. Taken from different sources, the long list of relevant parameters influencing the form pressure, discussed in Chapter 1, can be regarded as generally agreed upon worldwide. In addition some phenomena more specifically regarding SCC is reported in literature and should be further investigated. Thus, a number of topics, divided between laboratory and field studies, respectively, are recommended to be addressed in future research.

9.2.1 Laboratory studies

By using the developed methodology, i.e., the one for SCC structural build-up (reversible and irreversible) and the one for form-pressure measurement, the influence of the following parameters should be established:

- Temperature. Both the dispersion mechanism of superplasticizer molecules and as the Brownian motion depends on the temperature. In general a lower temperature decreases the intensity of both these mechanisms, i.e., flocculation (or coagulation) rate and dispersing mechanisms. This is important for the prediction of thixotropic behaviour at the normal variation of temperature in different seasons of the year.

- Cement type. Besides the two Swedish cement types used in this project a broader variation in terms of clinker composition and fineness should be included in order to make the knowledge of this parameter more general.

- Cementitious materials. Even though not so often used in Sweden, cementitious materials like fly ash, blast furnace slag and silica fume should be investigated as additives. Also this aspect would make the validity of the knowledge broader and more general.

- Thixotropy enhancing agents, TEA. This kind of chemical admixture has been reported to influence the thixotropic behaviour of mortar, see Khayat et al. (2002), and possibly more admixtures having these properties will be produced in future. Here, the advanced chemical industry and research institutions could play an important role by using their knowledge on nanotechnology in tailor making new molecules and polymers.

- Viscosity enhancing agents, VEA. The stability of SCC can be achieved with added powder materials, with VEA or with a combination of both methods. The product included in this project showed to increase the demand for superplasticizer so that the thixotropy in fact decreased. But there are more products to be investigated.

- The difference between the structural build-up of disturbed and undisturbed SCC (as discussed in Paper 4) should be further investigated and quantified.

- Comparing different methodologies. The used methodology of characterising the time dependent static yield stress by performing consecutive stress-strain measurements should be systematically compared with “loop-test” and “structural breakdown at constant shear rate”
(both described in Section 3.3). The possible correlation between these different approaches is important to establish for a wider understanding of the reversible thixotropic phenomenon (and the irreversible slump-loss).

9.2.2 Field studies

There are some obvious parameters to be studied in field or in a field-like setup and the following are here recommended to be addressed:

- Form characteristics. The geometry, form surface, form permeability, form releasing agent and form stiffness are known to influence the form pressure as discussed in Chapter 1. And since all these parameters normally differ from application to application (housing and civil engineering structures) and from time to time (because of aging and wearing) it has to be investigated how they influence the pressure relative to the structural build up of the concrete.

- Reinforcement. The influence of reinforcement configuration and of how congested it is should be investigated. This is a parameter varying much depending on application and if this is influencing the form pressure significantly, it must be taken into account and included in a model for design loads.

- Disturbances. The reversible time-dependent structure, i.e., the true thixotropical structure of SCC, is sometimes said to be a weak structure relatively easy to break through disturbances, e.g. vibrations from machines and vehicles at the site, see Leemann et al. (2006) and Tejeda-Dominguez (2005). It is most important to establish thorough knowledge of this phenomenon and how sensitive it is.
Chapter 10

References


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