KTH Architecture and the Built Environment

TIME DEPENDENT MATERIAL PROPERTIES OF SHOTCRETE FOR HARD ROCK TUNNELLING

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Abstract

In this thesis different mechanical properties for shotcrete (sprayed concrete) such as compression strength, bond strength, bending tensile strength, elastic modulus, free and restrained shrinkage as a function of its age was investigated. One of the main issues was to investigate the difference between ordinary cast concrete and shotcrete. Reliable material data for young and hardening shotcrete is scarce which in the past have made such comparisons difficult. Also, less accurate data representative for cast concrete has often been used in numerical modelling and design analyses. The focus of the project has particularly been on the properties bond strength and restrained shrinkage for which two new testing methods has been developed and evaluated. Microstructural studies have also been performed as a complement to the bond strength testing.

The bond to rock is one of the most important properties for shotcrete used as rock reinforcement. During the very first time after spraying the physical properties and the bond to the rock depend on the set accelerator and the micro structure that is formed. The investigation of early age bond strength of shotcrete is of great importance both from a production perspective and a safety perspective. The newly developed method was tested and evaluated and proved that it can be used for bond strength testing already from a couple of hours after shotcreting. The bond, or adhesion, depends on several factors such as texture of the rock, the type of accelerator, application technique, etc. In this work the development of the microstructure in the interfacial transition zone (ITZ) and strength of the bond was investigated. The results show that the bond strength is related to the hydration process, i.e. the strength gain of the shotcrete. The early development of the ITZ was here studied using a scanning electron microscope (SEM) making it possible to observe changes over time, before and after proper cement hydration.

Restrained shrinkage cracking of shotcrete, especially in the case of shotcrete sprayed on soft drains that are parts of a tunnel lining not continuously bonded to the rock, can be detrimental for the sustainability of an infrastructure tunnel system. Maintenance and repair costs can be high over time. It is shown that the developed test method realistically captures the behaviour of shotcrete drains on hard rock in situ. The method can be used in the evaluation of different technical solutions for avoiding or minimizing shrinkage cracks in shotcreted soft drains. It can also be used to assess the performance of shotcrete fully bonded to a rock surface, with respect to the ability to prevent cracking or to distribute possible shrinkage damage into several fine cracks instead of one wide.

Keywords: : Shotcrete, rock, granite, bond strength, compressive strength, pull-out testing, failure modes, interfacial transition zone, micro structure, ettringite, set accelerator, shrinkage, drains, glass fibres, laboratory testing, tunnels & tunnelling

Sammanfattning (in Swedish)

I föreliggande avhandling har olika mekaniska egenskaper för sprutbetong så som tryckhållfasthet, vidhäftningshållfasthet, böjdraghållfasthet, elasticitetsmodul, fri och förhindrad krympning som funktion av ålder undersökts. En av huvudfrågorna som studerats har varit skillnaden mellan ordinär, gjuten betong och sprutbetong. Tillförlitliga materialdata för ung och uthärdad sprutbetong är bristfälliga vilket har gjort sådan jämförelse svår. Även mindre representativa data för gjuten betong har ofta använts vid numerisk modellering och analys av utformning. Fokus hos projektet har särskilt varit riktat mot egenskaperna vidhäftningshållfasthet och förhindrad krympning för vilka två nya provningsmetoder utvecklats och utvärderats. Mikrostrukturella studier har även utförts som komplement till provningen av vidhäftningshållfasthet.

Bindningen mot berg är en av de viktigaste egenskaperna för sprutbetong som används vid bergförstärkning. Under den första tiden direkt efter sprutning är den fysikaliska bindningen mot berg beroende av tillstyvnadsacceleratorn och den mikrostruktur hos sprutbetongen som acceleratorn gett upphov till. Undersökningen av tidig vidhäftningshållfasthet hos sprutbetong är av stort värde både ur ett produktionsprocessperspektiv men även ur ett säkerhetsperspektiv. Den nyligen utvecklade metoden har provats och utvärderats och visat sig vara användbar för vidhäftningshållfasthet redan ett par timmar efter sprutning. Bindningen eller adhesionen beror av flera olika faktorer, så som texturen hos berget, typ av tillstyvnadsaccelerator, applikationsteknik mm. I detta arbete har mikrostrukturens utveckling i övergångszonen mellan berg och cementpasta och bindningens styrkeutveckling undersökts. Resultaten visar att vidhäftningshållfastheten är relaterad till hydratationsprocessen, d.v.s. styrkeutvecklingen hos sprutbetongen. Den tidiga utvecklingen av övergångszonen studerades med hjälp av svepelektronmikroskop, vilket medgav observation av strukturella förändringar över tid både före och efter den riktiga cementhydratationen.

Förhindrad krympning hos sprutbetong, speciellt sprutad på mjuka dräneringsmattor ingående i ett tunnelsystem där kontinuerlig bindning till berget ej föreligger, kan vara skadlig för beständigheten hos tunnelsystemet. Underhålls- och reparationskostnader kan bli höga över tid.

Den utvecklade provningsmetoden uppvisar ett realistiskt sätt att fånga beteendet hos en dräneringskonstruktion in situ. Metoden kan användas i utvärderingen av olika tekniska lösningar i syfte att förhindra eller minimera sprickbilning i mjuka dräneringskonstruktioner. Metoden kan även användas att bedöma utförandet av sprutbetong fullt vidhäftad till en bergyta, med hänsyn till förmågan att förebygga uppsprickning eller att fördela möjlig krympningsskada på fler fina sprickor istället för en bred.

Preface

This work has been carried out at Kungliga Tekniska Högskolan, Div. of Concrete Structure (KTH – Royal Institute of Technology).

The presented laboratory investigations constitute part of a project that studies the material properties of young and hardening shotcrete. The project is supported by *BeFo*, The Rock Engineering Research Foundation, *Formas*, the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, *SBUF*, the Development Fund of the Swedish Construction Industry and *Trafikverket*, the Swedish Transport Administration. Their support is hereby greatly acknowledged!
CBI and Vattenfall Research & Development are also acknowledged for providing important research infrastructure in the form of laboratory facilities.

First of all, I express my sincere gratitude to my supervising group at KTH consisting of main supervisor Prof. Anders Ansell, Prof. em. Jonas Holmgren, and adjunct Prof. Björn Lagerblad for their guidance, support and enthusiasm.

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Uppsala, May 2014

Lars Elof Bryne

List of notations

$A_{granite}$	is the granite cross section area
A_{shcr}	is the shotcrete cross section area
E_{cm}	is the shotcrete average elastic modulus
$E_{granite}$	is the granite elastic modulus
f_{ck}	is the shotcrete characteristic compressive strength
f_{cm}	is the shotcrete average compressive strength
$f_{cm,cube}$	is the average shotcrete cube strength
f_{ctm}	is the shotcrete average tensile strength
$f_{ctm,fl}$	is the shotcrete average flexural crack strength
f_{cb}	is the shotcrete bond strength
h	is the height of test beams
m	is the elasticity ratio
N	is the normal force acting on the granite cross section
RH	is the relative humidity
t	is the shotcrete age in days
a, b, c	are constants
d, e, f	are constants
g, h, i	are constants
h	is the relative overlay thickness
ε_L	is the strain at the lower gauge position

ε_{M}	is the strain corresponding to the bending moment
$\varepsilon_{max/min}$	is the maximum tensile (positive) or compressive (negative) strain
ε_{min}	is the maximum compressive (negative) strain
ε_{N}	is the strain corresponding to the normal force
ε_{sh}	is the shotcrete free shrinkage
ε_{shcr}	is the shotcrete strain
ε_{U}	is the strain at the upper gauge position
σ_{ctm}	is the shotcrete average tensile stress
σ_{max}	is the maximum stress
ψ	is the degree of constraint

List of papers

This thesis is based on the following research articles, which are referred to in the text by their roman numerals:

I. Bryne, L.E., Ansell, A., Holmgren, J. 2013 Laboratory testing of early age bond strength between concrete for shotcrete use and rock. *Nordic Concrete Research, 47, 81-100.*

II. Bryne, L.E., Ansell, A., Holmgren, J. 2014 Laboratory testing of early age bond strength of shotcrete on hard rock. *Tunnelling and Underground Space Technology, 41, 113-119.*

III. Bryne, L.E., Lagerblad, B. Interfacial transition zone between young shotcrete and hard rock. *Submitted to ACI Materials Journal, May 2014.*

IV. Bryne, L.E., Ansell, A., Holmgren, J. 2014 Investigation of restrained shrinkage cracking in partially fixed shotcrete linings. *Tunnelling and Underground Space Technology, 42, 136-143.*

V. Bryne, L.E., Ansell, A., Holmgren, J. 2014 Shrinkage testing of end-restrained shotcrete on granite slabs. *Magazine of Concrete Research, DOI:10.1680/macr.13.00348.*

The planning and performance of laboratory work have been performed by Bryne in all the papers. The SEM study in Paper III is done by Lagerblad and Bryne. During the whole project the co-authors have guided the planning, work, data evaluation and writing of the papers with comments and revisions.

As complement to the publications mentioned above, some additional publications have been made during the project. These publications are:

- Bryne, L.E., Ansell, A. 2011. Restrained Shrinkage Tests of Fibre Concrete for Shotcrete Applications in Hard Rock Tunnels. In: *Proceedings of the XXI Symposium on Nordic Concrete Research & Development, Hämenlinna.* Norsk Betongforening, Oslo, Norway, pp. 489-492.

- Bryne, L.E., Holmgren, J., Ansell, A. 2011.Experimental investigation of the bond strength between rock and hardening sprayed concrete. In: *Proceedings of the 6th International Symposium on Sprayed Concrete, Tromsö.* Norway, September 2011, pp. 77-88.

- Bryne, L.E., Ansell, A. 2012. Laboratory testing of the bond strength between shotcrete and rock. In: *fib Symposium 2012, Concrete Structures for Sustainable Community; Stockholm*; Sweden; 11 June 2012 through 14 June 2012.

- Bryne, L. E., Lagerblad, B. 2012. Texture and bond at the interfacial zone between rock and sprayed concrete. In: *fib Symposium 2012: Concrete Structures for Sustainable Community; Stockholm*; Sweden; 11 June 2012 through 14 June 2012.

- Bryne, L. E., Ansell, A., Holmgren, J. Early age bond strength between hard rock and hardening sprayed concrete. To be presented at *the 7th International Symposium on Sprayed Concrete, Sandefjord*, June, 2014.

- Bryne, L. E., Ansell, A. Laboratory testing of early age shotcrete bond strength. To be presented at *the XXII Symposium on Nordic Concrete Research & Development, Reykjavik,* August 2014.

- Ansell, A., Bryne, L. E., Holmgren, J. Testing and evaluation of shrinkage cracking in sprayed concrete on soft drains. To be presented at *the 7th International Symposium on Sprayed Concrete, Sandefjord*, June, 2014.

- Ansell, A., Bryne, L. E. Laboratory evaluation of shrinkage in shotcrete on soft drains. To be presented at *the XXII Symposium on Nordic Concrete Research & Development, Reykjavik*, August 2014.

- Lagerblad, B., Bryne, L. E. Texture and bond at the interfacial zone between hard rock and sprayed concrete at early age hardening time. To be presented at *the 7th International Symposium on Sprayed Concrete, Sandefjord,* June, 2014.

- Lagerblad, B., Bryne, L. E. Cement hydration and development of texture and bond at interfacial zone between hard rock and shotcrete. To be presented at *the XXII Symposium on Nordic Concrete Research & Development, Reykjavik*, August 2014.

CONTENTS

1. Introduction

A variation of applications for shotcrete (sprayed concrete) can be found in both the construction and the mining industry. In hard rock tunnelling shotcrete is one of the most important materials used to stabilize and secure the rock. Today, the building process within densely populated cities must live up to the societal environmental awareness, making underground infrastructure systems a competitive solution. In e.g. Sweden this means construction of large and complex tunnel systems through hard rock which are designed for a minimum of maintenance costs throughout the operative life-span, see e.g. Sturk et al (1996), Holmgren (2010) and Ansell (2010). This puts focus on the quality and reliability of the shotcrete based support systems which must function with a minimum of inspections and maintenance work that often cause problematic traffic interruptions. Quality shotcrete linings and other shotcreted structures require a high degree of workmanship during spraying as well as sophisticated material and other technical design.

1.1 Background

Securing of the rock mass during tunnelling through hard rock is done with various combinations of rock support elements. Shotcrete, fibre reinforced as well as un-reinforced, is one of the most important materials that are used. Rock surfaces in tunnels and other subspace constructions are often secured with shotcrete immediately after the excavation blasting to prevent fallout of smaller blocks and to secure the arch shape of the tunnel and thereby its capacity to carry weight of the surrounding rock mass, see Figure 1.1. Shotcrete must often be able to carry loads and withstand disturbances very early after spraying. Movements in the rock mass, sudden climate changes and vibrations from machines and construction work may cause damage that threatens the performance of the hardened shotcrete. One important case is vibrations from blasting during tunnelling which may lead to full or partial de-bonding between shotcrete and rock (Ansell, 2004). It is vital for the safety of a tunnel that shotcreted sections can be subjected to vibrations and still continue to provide accurate support. Numerical analyses (Ansell, 2005 and 2007) have shown that but also highlighted the need for accurate data on e.g. early bond strength as input for accurate analyses. It has been shown that the relation to strength growth for important material parameters such as modulus of elasticity and tensile strength is important for the performance of a hardening concrete lining (Ahmed and Ansell, 2014). Thus, when modelling early age carrying capacities for a tunnel lining during the production process it is vital to have reliable material data for the shotcrete as input. However, there is very little accurate material data for young shotcrete available, i.e. published, which makes it difficult to perform accurate design of these rock support systems. Material data for conventional, cast concrete is often used as substitute but although the basic material compositions are similar the method of placement gives shotcrete unique material performances. For example, the rate of bond strength growth for shotcrete differs from that of other strengths for cast concrete that do not contain a set accelerator. Also the use of other additives and the underground climate and temperatures also affect the strength growth ratio of shotcrete.

In general the quality of a shotcrete lining is much dependent on the adhesion properties of the interaction between shotcrete and rock wall. Macroscopically, the bond strength is in focus and microscopically the interesting issue is how the interfacial transition zone (ITZ) is formed. Where the environment is more extreme, as for example in transmissive zones in the rock where a lot of water flows, drainage systems together with the shotcrete lining make a more complex system. The essential focus is on crack limiting approach. In the interaction/joint action between rock wall, drainage mats and shotcrete, restrained shrinkage is in focus. One essential part of this development is the interaction between different types of fibres and cement paste to withstand the stresses that appear during the first stages and minimize or avoid cracking from shrinkage during the shotcrete hardening process. Experiences from earlier inspections of larger highway projects e.g. Södra länken (the Southern Link) in Stockholm show that large average crack widths are common in hardened shotcrete (Ansell, 2010). When designing a shotcrete drain a shrinkage crack appearing at an unsuitable place can increase the design moment with up to 50% (Holmgen, 2014), which when accounted for in the design will increase the total cost of the structure. The durability of steel fibre reinforced shotcrete depends on a minimum width of possible cracks due to the risk for corrosion. Wide cracks will also affect the load carrying capacity and stress distribution within the shotcrete structure. Preliminary tests with combinations of steel and glass fibres, see Holmgren and Ansell (2008a-b) and Bryne and Ansell (2011), have indicated that it is possible to distribute shrinkage strain resulting in many smaller instead of few wide cracks. The ability to model these complex situations would be a much helpful tool in the design and future development of modern infrastructural systems. Thus, it is not recommendable to base design and analysis of shotcrete performance on material properties obtained for cast concrete. Instead, focus must be put on obtaining reliable material data for young and hardening shotcrete, especially for the bond strength between rock and shotcrete.

Figure 1.1. Tunnel lining of steel fibre reinforced shotcrete. Picture by courtesy of BESAB, Gothenburg, Sweden.

1.2 Outline of the thesis

This thesis is summarized as the synthesis of five appended papers. Most of the results are presented in the different papers.

Paper I and II deals with adhesion properties with mainly bond strength as leading property. Paper III is also dealing with adhesion issues but in a more microscopic scale. The microstructure of the interfacial transition zone between the rock wall and the shotcrete is examined. Paper IV and V treat restrained shrinkage problems especially for drainage constructions where adhesion does not exist.

Chapter 1 presents background and objectives of the thesis.

Chapter 2 describes shotcrete in tunnelling with focus on shotcrete drains.

Chapter 3 describes shotcrete as a material, how it is processed both in general but also according to this study. The interaction between shotcrete and hard rock is also explained and especially how shotcrete is used in so called drainage constructions.

Chapter 4 presents results that are compiled from the different Papers. Tests from both cast and sprayed concrete are presented. Results from standard testing are presented for compression, flexural bending and free shrinkage. Results from new test methods are also presented for bond strength, microscopy of the ITZ and restrained shrinkage of both cast and sprayed concrete or shotcrete.

Chapter 5 discusses the results focused on bond strength and restrained shrinkage for both cast and sprayed concrete or shotcrete.

Finally, chapter 6 presents conclusions that can be drawn from the different studies. Future work is also discussed in the chapter.

1.3 Objectives

The ultimate goal of the work presented in this PhD thesis was to gain knowledge of time dependent material properties of shotcrete for hard rock tunnelling, which can be used to attain a more cost effective design of rock support, a reduced shrinkage cracking of shotcrete at early age, as well as a more secure production process of hard rock tunnels.

The main objective was to investigate different mechanical properties such as compression strength, flexural strength, bond strength and elastic modulus for shotcrete as a function of age. The strategy for the study of these different mechanical properties has been to use standardized methods as far as possible and to test new methods, when the standardized ones are unsufficient or not possible to use. The obtained material data would more accurately describe the shotcrete behaviour than data representative for ordinary cast concrete, which often has been used as a substitute in the past. The information was aimed for use in design, analysis and advanced numerical modelling of tunnels and different underground structures constructed in hard rock. One of the main issues was also to investigate the difference between ordinary cast concrete and shotcrete, and especially how the cement hydration properties and the use of set accelerators affect the results.

A second objective was to investigate and measure the bond strength between shotcrete and hard rock and to suggest and evaluate a suitable method for testing at early shotcrete ages. Studies of the microstructure at the interface between rock and shotcrete were also included. The aim was here to find any evidence of physical or chemical bonding at the interfacial transition zone between shotcrete and rock.

A third objective was to investigate free and restrained shrinkage of young and hardening shotcrete and the risk of cracking. Focus was put on the situation that arises with shotcrete sprayed on top of soft elastic drains. One part of the investigation was to design a test method that could capture the behaviour of a shrinking shotcrete slab that bonds to a surface that does not restrain the shrinkage deformation between the fixed ends of the slab, as would be the case for shotcrete over drains in situ.

The extent of the study has been restricted compared with what would have been desirable with regard to the large number of parameters which affects the properties of a shotcrete under realistic conditions. The tests have therefore been performed in laboratory environments but with comparisons to known in situ data. However, some tests have been performed in lower temperature conditions. Most of the test samples are in small scale, as existing standardized test methods have been used as far as possible. The focus has been on conditions for hard rock tunnelling, e.g. as for larger Swedish civil engineering projects with construction work in granite. Thus, the studied shotcrete type is based on a standardized mix that is adapted for use with the wet mix method of shotcreting. Variation in material composition is given through addition of steel and glass fibres and the use of set accelerator, which is not included in the mix for the cast test specimens.

2. Shotcrete in tunnelling

Shotcrete is used to support fresh areas of hard rock during tunnelling and is often applied immediately after a sequence of blasting excavations to provide conditions for the rock to carry itself. The main effect is that downfall of small blocks and keystones is held back, thus securing the arch shape of the tunnel during the movements that takes place in the rock mass that seeks a new equilibrium. An early applied shotcrete layer thus seals the rock surfaces of tunnel walls and ceilings through the bonding effects. It is also believed that there is a mortar effect, which is the result of the impact velocity through which the shotcrete penetrates cracks and joints and acts as a mortar.

2.1 Wet sprayed shotcrete

The difference between ordinary cast concrete and sprayed concrete or shotcrete is the method of placement which in the latter case is projection using compressed air instead of casting and vibrating. Shotcrete has been in use for a period of over 100 years, with the dry mix method as the original method. With the dry method a slightly moistured cement mortar mix is blown by compressed air through a hose towards a nozzle, where the material is wetted before being projected onto e.g. a rock surface. The method has a limited capacity and also produces a relatively high amount of dust. It is today mostly used for small scale construction work and repairs. The wet mix method was introduced in the 1950s and is now the most common method for large scale work, such as rock support. With the wet method a ready mix concrete is pumped towards the nozzle from where compressed air is used for the projection. The method allows a significantly higher capacity and the dust formation is less than with the dry method. However, to facilitate pumping and spraying the water-cement ratio must normally be higher than for the dry method and accelerating additives must therefore be used to obtain a rapid stiffening on the target surface. Thus, the use of set accelerator to cause a more or less instant hardening of the shotcrete is an important feature that separates shotcrete from cast concrete. Nowadays the largest amount of wet sprayed shotcrete is applied robotically but manual application is also in use for smaller scale works. In this project wet mixed shotcrete is studied, including tests performed with manually sprayed specimens. It should be noted that the quality of the shotcrete produced depends on the type of target surface, i.e. type of rock, condition of the rock surface, method of spraying, i.e. wet-mix or dry-mix method, and to a high degree also on the skill of workers handling the spraying equipment. For this work the pumping machine used was a Putzmeister, THOM-KATT (TK 25) and the accelerator pump was an Aliva AL-403, with the set accelerator added in the nozzle. Spraying of the test samples is shown in Figures 2.1–2.2. For further details on the shotcrete process, see e.g. (Höfler and Schlumpf, 2004).

Figure 2.1. Operator spraying a test box with shotcrete, from which specimens for compression and flexural strength test were later cut out.

Figure 2.2 Concrete pumping machine, Putzmeister, THOM-KATT (TK 25).

2.2 Fibre reinforced shotcrete

There exists a large variation in material, shape and dimensions of fibres that can be used as reinforcement in cement paste, mortar and concrete. Due to the cost of the material fibre reinforcement cannot compete with conventional bar reinforcement in heavily reinforced structural elements such as beams and suspended slabs. It is also practically difficult to mix in sufficiently large fibre amounts without making the concrete porous and thus severely weakened in strength and durability. However, one exception is industry floors, where fibre reinforcement can be superior due to its ability to prevent cracking from shrinkage and fatigue, and this also motivates its use in shotcrete constructions. Steel is today the dominating fibre material and can be manufactured by wire drawing, cutting from bands or melt extraction. There are variations of the shape of the fibre in its longitudinal direction and different types of end anchors are also used. Typical steel fibres used with shotcrete in e.g. Sweden are 35 à 40 mm long, with diameters around ϕ0,5 mm and with bent ends. A longer and thinner fibre would be preferable, since the reinforcement effect, the ductility and thus also the economy is improved with such a fibre. Thinner and longer fibres do, however, cause problems during pumping and spraying. These types of steel fibres are macro fibres, as shown in Figure 2.3 that also give examples of synthetic, i.e. plastic, fibres. Steel fibre reinforced concrete was studied by Ding and Kusterle (1999; 2000). Further examples on fibre types is given in Table 2.1 which present a compilation of fibre types used in laboratory investigations of concrete and shotcrete shrinkage, see also Ansell et al. (2006).

Strain hardening in the cracked state is a desired property of the shotcrete material, which is possible if a sufficient amount of suitable fibres has been added to the concrete mix. In such a shotcrete material the tensile strength increases after the formation of the first crack, leading to the formation of several fine cracks instead of one wide. Ordinary steel fibre reinforced shotcrete usually has a fibre content not larger than 60 kg/m^3 (Holmgren and Ansell, 2008a), giving a strain softening behaviour and consequently only one, wide crack develops. Experience shows that in such cases the crack width e.g. due to shrinkage often exceeds what is acceptable considering durability, see e.g. Ansell (2010) and Ansell (2011). To distribute the strain and stress in shrinking concrete and shotcrete the use of various types of micro fibres is considered. The cross section areas of these are considerably smaller than of the macro fibres and the idea is that a large amount of fibres will be present in all sections of the shrinking structure. Existing micro fibres are made from synthetic, plastic materials but there are also carbon fibres and glass fibres, see e.g. Pihlajavaara and Pihlman (1977) and Swamy and Stavrides (1979) who present results for glass fibres with respect to shrinkage. The type of 6 mm glass fibres used in the tests here presented in Papers IV-V is shown in Figure 2.4. See also section 4.1.

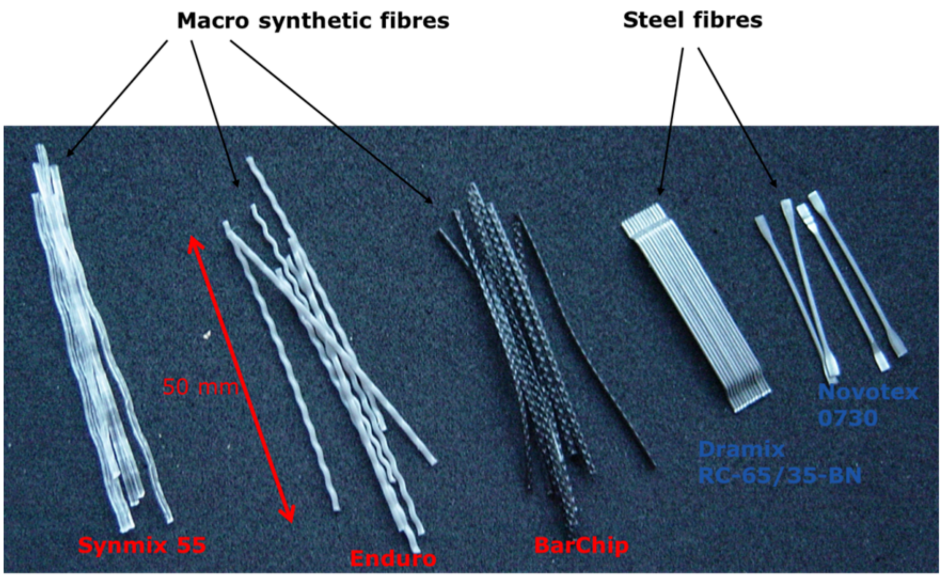


Figure 2.3. Macro fibres – steel fibres and synthetic fibres.

Figure 2.4. Micro fibres – here 6 mm long glass fibres.

Table 2.1. Examples of steel and synthetic fibres for concrete.

Type		**Length (mm)**	**Cross-section (mm)**	**Reference**
Steel fibres				
Smooth	Fibraflex	15,0	□0,035 flat	Mesbah& Buyle-Bodin (1999)
End-hooks	Dramix	35,0	ϕ0,55	Bryne & Ansell (2011)
End-hooks	Dramix	35,0	ϕ0,55	Malmgren et. al (2005)
End-hooks	Dramix	60,0	ϕ0,80	Westin et al. (1992)
End-hooks	Eurofiber	50,0	ϕ0,90	Westin et al. (1992)
End-hooks	Twincone	54,0	ϕ1,00	Westin et al. (1992)
Waved	Novocon Int.	25,0	ϕ1,20	Alekrish & Alsayed (1994)
Waved	Xorex	50,0	ϕ0,90	Westin et al. (1992)
Waved	Eurosteel	60,0	ϕ1,00	Westin et al. (1992)
Stamped	Hörle	70,0	ϕ0,70	Westin et al. (1992)
Twisted	Harex	31,8	ϕ0,84	Mangat & Azari (1990)
Synthetic fibres and glass				
PE	Spectra	6,4	ϕ0,028	Lim et al. (1999)
PE	Spectra	12,7	ϕ0,028	Lim et al. (1999)
PE	Allied Signal Co	12,7	ϕ0,038	Kong et al. (2003a)
PVA	Kuraray Co. Ltd.	6,0	ϕ0,014	Li et al. (2001)
PVA	Kuraray Co. Ltd.	12,0	ϕ0,039	Li et al. (2001)
PVA	Kuraray Co. Ltd.	12,7	ϕ0,048	Kong et al. (2003b)
Poly-olefin	Shogun, BarChip	48,0	*	Aziz (2005)
*	BarChip Kyodo	48,0	ϕ0,900	Hauck et al. (2004)
*	Tunnel Fiber	42,0	*	Aziz (2005)
Glass	Saint Gobain	6,0	ϕ0,014	Bryne & Ansell (2011)

PE = Polyethylene
PVA = Polyvinyl alcohol
PP = Polypropylene

□ = Square cross-section
* = Unknown

2.3 Shotcreted drains

Different alternatives for collection of infiltrating water that may be considered in the design of hard rock tunnels are e.g. shotcreted drains, screen drainage and full lining, see e.g. Sturk et al. (1996) and Holmgren (2010). A typical shotcreted drain used in the Scandinavian countries is shown in Figure 2.5. This construction consists of a plastic mat, with closed pores and thus unable to absorb water, which is covered with fibre reinforced and in some cases also unreinforced shotcrete. The shotcrete in the drain is fixed at its edges by bond only and is otherwise free to move. Due to this it is sensitive to shrinkage and to over- and underpressure, which occur in traffic tunnels when vehicles pass. In road tunnels the pressures are moderate but in railway tunnels, where high-speed trains pass, these can be considerably higher, see Holmgren (1994) and Bäck and Oscarsson (1995). In this thesis the shrinkage resistance of shotcreted drains is studied, see Papers IV-V. The case with a free shotcrete slab with fixation at the ends leads to tensile stresses caused by restrained shrinkage. There is a risk for cracking that depends on the growth rate of the tensile strength and elastic modulus, but also on the creep properties of the shotcrete. In some cases multiple drains are placed side by side to cover tunnel lengths up to 20-30 m, as shown in Figures 2.6–2.7. In such drain structures cracks up to several millimetres wide may develop (Holmgren and Ansell, 2008b), resulting in early corrosion and e.g. a decreasing capacity to withstand fluctuation air pressure from passing vehicles (Holmgren and Ansell, 2008a).

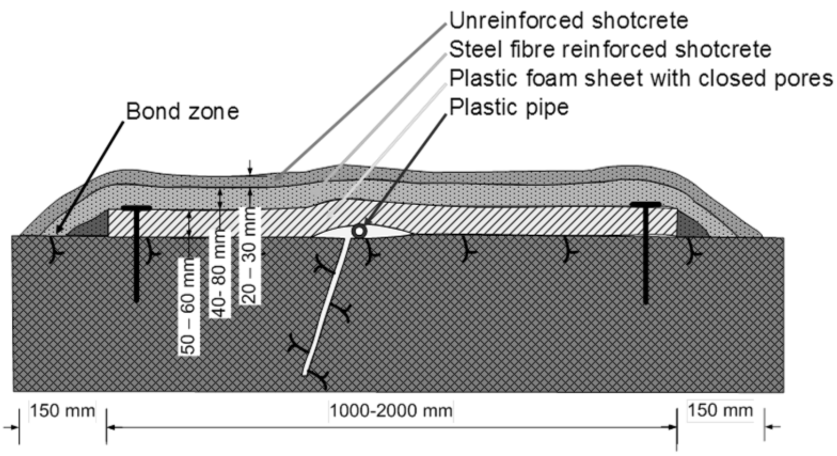


Figure 2.5. Shotcreted drain on rock – one strip of drain mat covering cracks in the rock. From Holmgren and Ansell (2008b).

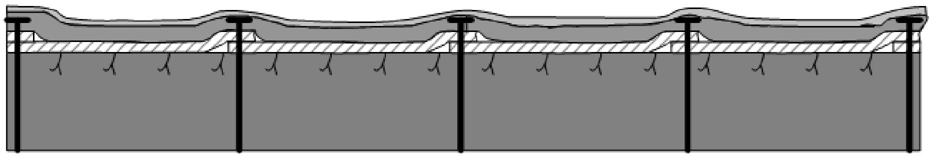


Figure 2.6. Long section of shotcreted drains on rock – drain mats side by side with overlaps. From Ansell (2010).

Figure 2.7. The Southern Link road tunnels, constructed with shotcreted drains. Photo provided by the Swedish Road Administration.

3. The shotcrete material

In comparison with ordinary cast concrete shotcrete has unique material properties, due to the method of placement, i.e. projection using compressed air, but also to the use of set accelerators. Although the composition of shotcrete is basically the same as of cast concrete there are relatively fast cement reactions that affect the material strength growth but also increase the shrinkage which e.g. may lead to severe loss of shotcrete-rock bond (Holmgren et al., 1997). It is therefore not recommendable to base design calculations and analyses of shotcrete performance on material properties obtained for cast concrete. However, published, reliable material data for young and hardening shotcrete is scarce, due to difficulties in performing testing of very young shotcrete using existing testing methods.

3.1 Structure and chemistry

Microstructural studies of different materials are well established discipline within scientific work, often in combination with other material studies as strength development and fracture mechanics etc. The young shotcrete structure and chemical composition is here studied in Paper III. Scanning Electron Microscopy (SEM) is one of the leading methods in use for different materials and also for concrete. The micro structure of shotcrete can be seen as a SEM micrograph in Figure 3.1. Chemically the main difference between ordinary cast concrete and shotcrete is the set accelerator that is added to the concrete mix in the nozzle during spraying, especially in the wet mix method. The set accelerators will not directly interfere with the major cement reactions (Lagerblad et al., 2010). Instead, the set accelerator will react with the pore solution of the young cement paste during the dormant period. Alkali-free set accelerator is currently the dominating type at the market. Common aluminium salts that can be used as alkali-free set accelerators are:

- Aluminium sulphate salt $Al_2(SO_4)_3$
- Amorphous aluminium hydroxide $Al(OH)_3$.

These react with the pore solution in a similar way and form a structure of ettrigite. The chemical formula of ettringite is as follows:

$$3CaO.Al_2O_3.3CaSO_4.32H_2O.$$

It is this ettringite structure that forms immediately after spraying and gives the instant hardening and a compression strength of 2-4 MPa. After 10-12 hours the major cement reactions start from this ettringite structure.

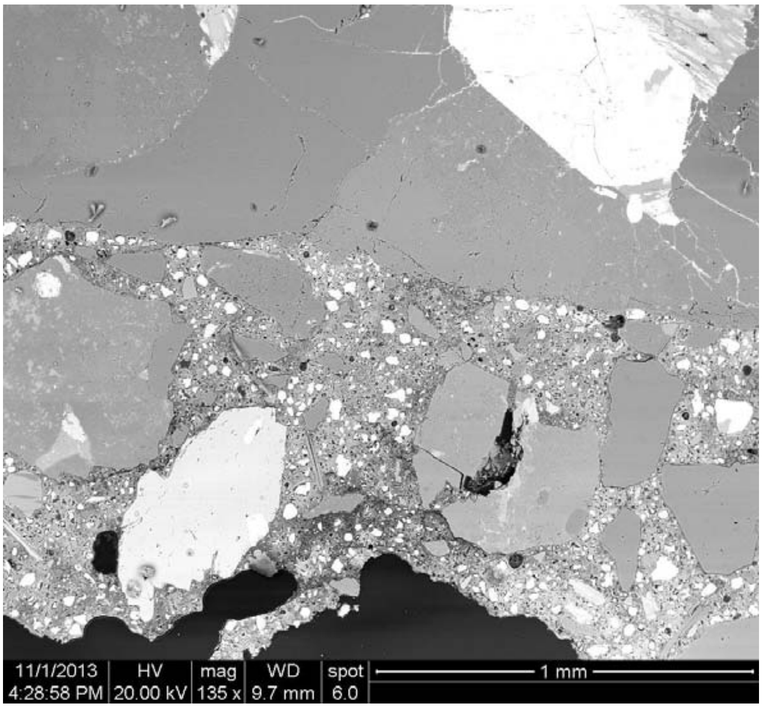


Figure 3.1. The microstructure of shotcrete and interaction with granite, or hard rock.

The four components regarded as the major constituents of cement are (see Table 3.1):

Calcium oxide ($CaO = C$)

Silicate oxide ($SiO_2 = S$)

Aluminium oxide ($Al_2O_3 = A$)

Ferric oxide ($Fe_2O_3 = F$).

Table 3.1. Main compound of cement.

Name of compound	Oxide composition	Abbrevation
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	$3CaO.Al_2O_3.Fe_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF

3.2 Shotcrete – rock interaction

The interfacial transition zone (ITZ) between aggregate or fibre and cement paste matrix is important for optimising the shotcrete material. The interface between shotcrete and a rock wall is also connected by an ITZ. Cracking of concrete is generally believed emanating from the properties of the ITZ (van Mier and Vervuurt, 1999). Besides the evaluation of fracture surfaces, studies of interfacial zones between different materials are of great importance. Studies of the ITZ between cement paste and aggregate have earlier been done by Rehm et al. (1977). Diamond (2004) has studied the micro structure of cement paste and concrete in a purely qualitative manner in an attempt to illustrate the important features of hydrated cement paste as a 'visual primer'. Figure 3.2 shows light microscopy photos of the ITZ of shotcrete from a sample taken after a bond strength test. The left side in the photo was in contact with the rock wall. The interaction between shotcrete and rock is mechanically tested through bond strength testing or adhesion strength testing. Examples of bond strength from pull-out testing of fully hardened shotcrete, sprayed on different substrates are summarized in Paper I. Primarily, the corresponding total bond strength between two materials is utterly determined by these contributing mechanisms and the surface area over the two materials contact. Secondary mechanisms or factors as e.g. microstructure can also contribute to the overall strength and reliability of a bonding situation. In young, sprayed concrete the microstructure and bond strength will change over time as a result of the progress of cement hydration.

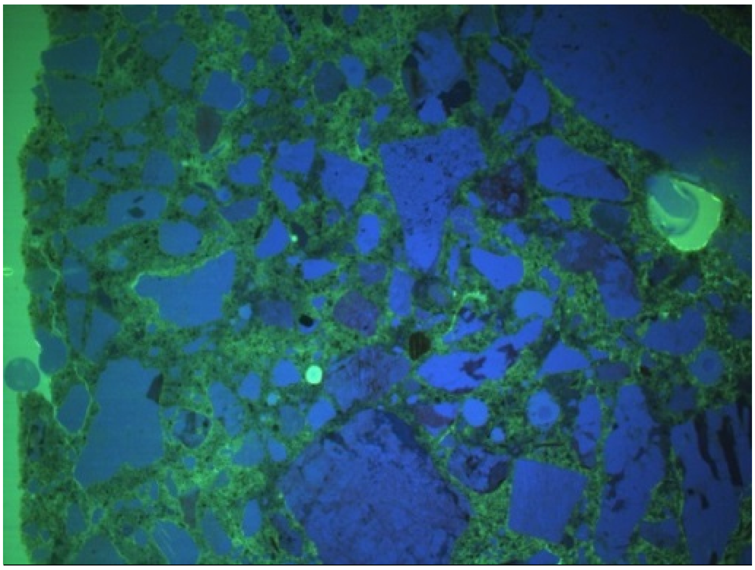


Figure 3.2. Interfacial transition zone (ITZ) in shotcrete. Left side in photo is the former granite wall before bond strength testing (Magnification: side of the photo is 6.7 mm).

3.3 Free shrinkage

Experience from shrinkage of cast concrete, mortar and cement paste is important to consider in the study of shotcrete, due to the similarities in material composition. However, the shrinkage of shotcrete is often higher than of ordinary concrete due to the use of smaller size aggregates, higher cement content and set accelerators. Different types of shrinkage in shotcrete and the risks of cracking is summarized by Morgan and Chan (2001) who observed that plastic shrinkage appears in fresh concrete before it settles and starts to harden and is caused by moisture emission to the surroundings. One important type of shrinkage in the hardened state is drying shrinkage, caused by emission of moisture to the surroundings. Drying shrinkage is a longtime process that can occur during several years but around 70% occurs within the first three months (Toledo et al., 2005). Shotcrete that is exposed to early drying, i.e. within 12 hours to 7 days, is particularly sensitive and can crack due to shrinkage. It should be noted that concrete has a relatively low drying shrinkage compared to cement paste which is due to the restraint from the aggregates. In shotcrete autogeneous shrinkage can also appear, caused by hydration of cement paste when water is consumed, i.e. self-desiccation. The autogeneous shrinkage is often <0,1‰, which corresponds to around 10% of the simultaneous shrinkage due to longtime drying. Cracks caused by autogeneous shrinkage in shotcrete are rare, and the present study therefore focus on drying shrinkage, see Papers IV-V. Some relevant examples are summarized in Table 3.2 for further comparisons.

Table 3.2. Examples of shotcrete shrinkage observed during laboratory testing.

Fibres	Content	Shrinkage	Age	Reference
Free shrinkage				
Steel	0%	0,5‰	130 days	Ramakrishnan (1985)
	0,6%	0,7‰		
	1,0%	0,5‰		
	1,3%	0,5‰		
Steel	0% *	0,85‰	500 days	Mangat & Azari (1990)
	3,0% *	0,55-0,75‰		
Polypropylene	0%	1,3‰	365 days	Goodier et al. (2001)
	>0%	1,4-1,8‰		
Polypropylene	0,7-1,1%	0,5-1,3‰	37 days	Aziz (2005)
Restrained shrinkage				
Steel	0,5%	0,85‰	90 days	Malmgren et al. (2005)
Steel	0% **	0,55‰	40 days	Grzybowski & Shah (1990)
	0,25% **	0,40‰		
Polypropylene	1,0% **	0,45‰	40 days	Grzybowski & Shah (1990)

* = Cement paste ** = Concrete

3.3.1 Shrinkage in fibre reinforced shotcrete

In a state-of-the-art report Ramakrishnan (1985) summarizes shrinkage results for steel fibre reinforced shotcrete with three different fibre contents. The steel fibre type is ZP 30/50 and experiments with 0,6; 1,0 and 1,3 vol-% show total shrinkage of 0,7; 0,5 and 0,5‰, respectively, after 130 days. This shall be compared with 0,5‰ shrinkage for a corresponding un-reinforced shotcrete and it can also be noted that half of the total shrinkage was reached already after 5 days. Thus, there was little or no shrinkage reducing effect from these relatively low fibre contents. Results obtained with polypropylene fibres (PP) are presented by Goodier et al. (2001) from measurements of the free drying shrinkage during 365 days. There is no information about fibre contents given, but several shotcrete mixes are tested. Shotcrete was sprayed in panels of dimensions 100×500×500 mm^3, later cut into 75×75×229 mm^3 prisms. The results showed that the shotcrete with PP fibres had an increased shrinkage at 1,4–1,8‰ after 1 year, which shall be compared with 1,3‰ for a corresponding un-reinforced shotcrete. The results shall also be compared with measured free shrinkage for plastic fibre reinforced shotcrete by Azis (2005). Test specimen with dimensions 200×800×900 mm^3 was observed during 37 days. The results show a shrinkage of 0,5–1,3‰ and there were no significant difference between two different types of plastic fibres tested. The fibre contents was 8–12 kg/m^3, corresponding to 0,7–1,1 vol-%.

3.3.2 Shrinkage in fibre reinforced concrete and mortar

In comparison with the scarce results for shrinking shotcrete there exists much more published data on the free shrinkage of fibre reinforced cast concrete, for which a few references will be given for comparison in the following. An important comparison with cast concrete can be made with the relative extensive test series of free shrinkage on concrete and cement paste which has been performed by Mangat and Azari (1984, 1988 and 1990). The results consist of shrinkage measurements until 520 days, for different steel fibre types and contents up to 3 vol-%. The shrinkage reducing effect of the different types of steel fibres in falling scale were; crimped, hooked, melt extract, and smooth. The measured shrinkage at 500 days was within 0,55–0,75‰ with steel fibres, to be compared to 0,85‰ for the un-reinforced reference sample. It was also shown that half of the final shrinkage was reached already after 20–40 days. Free shrinkage of concrete reinforced with smooth, linear steel fibres is also reported by Chern and Young (1990) who measured the shrinkage development for 359 days. The optimal steel fibre content is concluded to be 2 vol-% and it is put forth that a high aspect ratio between length and width of the fibres gives less shrinkage. Some early tests on free shrinking reinforced steel fibre concrete specimens are summarized by Alekrish and Alsayed (1994). The summary begins with Swamy and Stavrides (1979) who conclude that adding steel fibres can reduce the drying shrinkage of the concrete with up to 20%. This shall be compared with the result from Grzybowski and Shah (1989) and Malmberg and Skarendahl (1978) who reported reductions of only 10%. For more results, see the compilation by Ansell et al. (2006).

3.4 Restrained shrinkage

The shrinkage of shotcrete is in principle always restrained due to the bond to the surface. One important exception is the above mentioned shotcreted drainage structures where the shotcrete is sprayed on an elastic surface. In a survey of shotcrete applications Melbye and Dimmock (2001) comment that only results from small size ring tests with concrete and unknown steel fibre types have been shown. However, based on these results the industry has accepted a steel fibre content of at least 40 kg/m^3 (approximately 0,5 vol-%) to limit the crack width to below 0,2 mm. There are few or no published investigations with shrinking shotcrete on rock surfaces. Cracking of shotcrete at restrained shrinkage has been studied through in situ test by Malmgren et al. (2005) with shotcrete applied on a concrete wall. The results showed that the restrained shrinkage can cause damage to the bond, which occurred on 40% of the total test area. It was noticed that the ability of the shotcrete to control and distribute cracks ceased due to bond failure. After 109 days the total crack width was around 0,3–0,8 mm in each of the sprayed test areas which were 250×2000 mm^2. Supplementary laboratory tests with un-restrained shrinking shotcrete with corresponding properties also showed that there was no difference in free shrinkage between un-reinforced and steel fibre reinforced shotcrete. The shotcrete reached around 0,7‰ shrinkage in 90 days, reaching half-ways already after 15 days. Some relevant examples are summarized in Table 3.2 for further comparisons. Carlswärd (2006) presented a new method for the measurement of restrained shrinkage of steel and plastic fibre reinforced concrete where the specimens had the shape of a slab with dimensions around 35×100×800 mm^3.

3.4.1 Shrinkage in steel fibre reinforced concrete

There are relatively few reports on restrained shrinkage of concrete and the shrinkage reduction effect from steel fibres. At conditions with restrained shrinkage of concrete many investigations focus on the cracks that can occur. In most laboratory investigations small-scale ring test specimens are used, with a concrete ring cast around a steel core that gives a restraining effect during shrinkage. Short reviews over the testing procedures and various types of rings used are given in Papers IV-V, and in the compilation by Ansell et al. (2006). A few important examples for further reference are however given in the following. One series of ring tests is presented by Grzybowski and Shah (1990) who investigated the effect of steel and PP fibres at different concrete ages and drying periods. After approximately 40 days the un-reinforced concrete showed a shrinkage of 0,55‰ after cracking while a corresponding steel fibre reinforced concrete (0,25 vol-%) reached approximately 0,40‰. In an earlier paper by Grzybowski and Shah (1989) it was also concluded that a content of 0,25 vol-% fibres reduces the crack width to 1/3 compared with a similar concrete without fibres. A fiber addition beyond 0,5 vol-% has on the other hand a very small effect. These conclusions were made with reference to tests done by Malmberg and Skarendahl (1978). From tests with steel fibre reinforced concrete for industrial floors Westin et al. (1992) report results of reduced restrained shrinkage after 9 weeks. It is shown that as best a 20% reduction could be reached, however the results show a relatively large variation. The mean value gave a reduction of 7% for the steel fibres and it is difficult to sort out if any of the six tested fibre types performs better than the other.

3.4.2 Concrete with synthetic and glass fibres

Tests with restrained shrinkage for concrete reinforced with synthetic, plastic fibres usually show larger crack widths and a much shorter time for initiation of first crack, compared to steel fibre reinforced concrete. The investigation by Grzybowski and Shah (1990) shows comparisons between tests with steel and synthetic fibres. It was observed that with 1,0 vol-% PP fibres the final shrinkage was 0,45‰, to be compared with 0,40‰ obtained with 0,25 vol-% steel fibres. With these contents of reinforcement similar crack widths of 0,11–0,17 mm were observed for fibres of the two materials. The test samples with synthetic fibres contained 1-2 cracks while the steel fibre samples showed proof of a higer ability to distribute shrinkage strain, with up to 3 cracks per sample. Similar results are shown by Mesbah and Buyle-Bodin (1999) who compared the effect of the two fibre materials on shrinking mortar, but in this case the steel reinforced samples showed twice as wide cracks as for the concrete samples. The crack widths obtained with synthetic fibres were comparable to those for the concrete samples. From tests with 0,1 vol-% PP fibre and 0,1-0,5 vol-% fibre of polyvinylalcohol (PVA) by Wang et al. (2001) it was concluded that 0,5 vol-% PVA fibres is needed to get two cracks in flat prisms specimens, instead of one. Restrained shrinkage testing of concrete slabs reinforced with various types of plastic fibres is presented by Balaguru (1994). With 0,15 vol-% micro fibres, a reduction of total crack area of 50% was achieved with PP fibres and over 90% with PE fibres. Of the tested longer types of fibres a maximal reduction of crack area was reached with PP fibres, around 85%, followed by nylon fibres with 75% and last polyester fibres that gave a reduction of 15%. It should be observed that the content of PP fibre was double that of the nylon fibres and three times that of the polyester fibre.

Few investigations of the effect from glass fibres on restrained concrete shrinkage have been reported. However, Swamy and Stavrides (1979) have investigated the effect of glass fibres and show that a fibre content of 1,5 vol-% delayed the crack initiation from 8 to 26 days. The number of cracks increased from one to three while the maximum crack width was reduced from 1,35 mm to 0,10 mm. From tests with up to 4,0 vol-% glass fibres in mortar Pihlajavaara and Pihlman (1977) have also observed a reduction in crack width, but with much wider cracks than for corresponding concrete.

4. Material properties from testing of young shotcrete

In this chapter all the results for the tests in papers I-V are presented and summarized. Details for each test procedure are given in the respective paper. Complete sets of test results are given for the presented material properties, as a complement to the papers where in some cases only examples are shown due to length restrictions. Some of the age-dependent parameters are also given for longer time spans. Material properties not tested but used in the papers for comparisons are also included in this compilation.

4.1 Density and slump

The concrete used in all tests (Papers I-V) is based on the more or less general recipe shown in Table 4.1. The most important deviation from the basic recipe is made in Paper IV and V where restrained shrinkage has been the issue, with different fibre mixes investigated giving the variance noted in Table 4.1. There is some variation according to aggregate and cement type, and for one of the tests in Paper I CEM II/A-LL 42.5 R has been used. For all other tests in Paper I-V, CEM I 42.5 N-SR 3 MH/LA is the general choice. As set accelerator Sigunit has been used, a liquid with a dry content of approximately 50%.

Table 4.1. General recipe and main ingredients for tested concrete.

Material	Density (kg/m^3)	Content (kg/m^3)
Cement	3150	495
Silika U/D	2230	20 [1]/19.8 [2,3]
Water	1000	220
Glenium	1100	4-8 [1]/3.5 [2,3]
Steel fibre Dramix	7800	See Table 4.2
Glass fibre	2600	See Tables 4.2-3
Fines	2650	0 [1,3]/157 [2]
Aggregate, 0-2 mm	2650	0 [1]/283 [2]/394 [3]
Aggregate, 0-8 mm	2650	1540 [1]/1135 [2]/1183 [3]

Results from [1] Ansell and Holmgren (2008b), [2] Bryne and Ansell (2011), [3] Papers IV-V

The results in Table 4.2 are taken from Paper IV which treats cast concrete with composition similar to shotcrete. The measured slump values are within 70-235 mm which is in accordance with the range for sprayability shown by Beaupré (1994). The results in Table 4.3 are from Paper V and present the slump test results for the sprayed concrete, i.e. shotcrete.

Table 4.2. Slump, density and compression strength of 28 days old 150 mm cast concrete cubes. With various combinations of steel and glass fibres.

Test no.	Steel fibres (kg/m^3)	Glass fibres (kg/m^3)	Slump test (mm)	Density (kg/m^3)	Compressive strength (MPa)
1 [1]	0	0	160	2277	79
2 [1]	50 (D30/05)	0	140	2339	78
3 [1]	50 (D30/05)	26 (6 mm)	70	2272	77
4 [1]	50 (D30/05)	26 (12 mm)	105	2231	68
5 [2]	0	0	230	2263	68
6 [2]	50 (D65/35)	0	235	2293	69
7 [2]	50 (D65/35)	5 (6 mm)	220	2297	68
8 [2]	50 (D65/35)	10 (6 mm)	190	2283	71
9 [2]	50 (D65/35)	15 (6 mm)	155	2283	68
10 [2]	50 (D65/35)	20 (6 mm)	70	2267	67

Results from [1] Ansell and Holmgren (2008b), [2] Bryne and Ansell (2011).

Table 4.3. Slump, density and compression strength of 28 days old, sawn shotcrete cubes and cast reference samples. With various contents of glass fibres.

Test no.	Steel fibres (kg/m^3)	Glass fibres (kg/m^3)	Slump test (mm)	Density (kg/m^3)	Compressive strength (MPa)
Cast ref.	0	0	210	2260	84
1	0	0	230	2267	67
2	0	5 (6 mm)	225	2230	66
3	0	10 (6 mm)	195	2190	60

4.2 Compressive strength

Compressive strength has been tested for both shotcrete (sprayed) and cast concrete. The compressive strength in both cases was tested according to *Swedish Standard SS-EN 12390-3:2009* (SSI, 2009b). Test specimens sawn from spray boxes for compressive and flexural tests are shown in Figure 4.1. In addition, the possibilities to use the stud-driving method (Hilti, 2001) was evaluated in a bachelor student project (Ryberg and Hedenstedt, 2012) within the frames of the doctoral project, see Paper IV. Early age compressive strengths for cast concrete and mortar, presented in paper I, are compared in Figure 4.2 with the strength for corresponding shotcrete and reference concrete, from Paper V. Equations for the fitted curves are given in Papers I, II and V, respectively. Results for cast concrete and shotcrete with and without glass fibres are presented in Paper V, for ages up to 28 days. These test series were continued with measurements also for 56 and 112 days of age, results of which are given in Figure 4.3. The expressions for the fitted curves, which can be compared to those given in Paper V, are given in Eqs. (4.1-4.4), for cast samples as:

$$f_{\text{cm,cube}} = 106,90\,\mathrm{e}^{-1,79/t^{0,51}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{4.1}$$

For shotcreted samples with 0 kg/m^3 glass fibres:

$$f_{\text{cm,cube}} = 76,68\,\mathrm{e}^{-1,70/t^{0,60}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{4.2}$$

For shotcreted samples with 5 kg/m^3 glass fibres:

$$f_{\text{cm,cube}} = 81,41\,\mathrm{e}^{-1,86/t^{0,53}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{4.3}$$

For shotcreted samples with 10 kg/m^3 glass fibres:

$$f_{\text{cm,cube}} = 65,95\,\mathrm{e}^{-1,82/t^{0,76}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{4.4}$$

Figure 4.1. Test specimens from spray boxes, for compressive and flexural crack strengths tests.

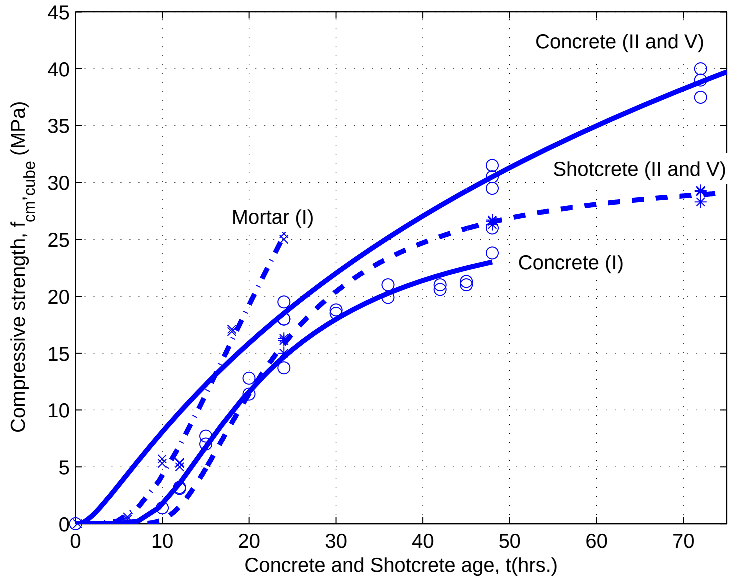


Figure 4.2. Compressive cube strength vs. age for cast concrete (Papers I, II and V) and shotcrete (Papers II and V). Compared to results for mortar (Paper I).

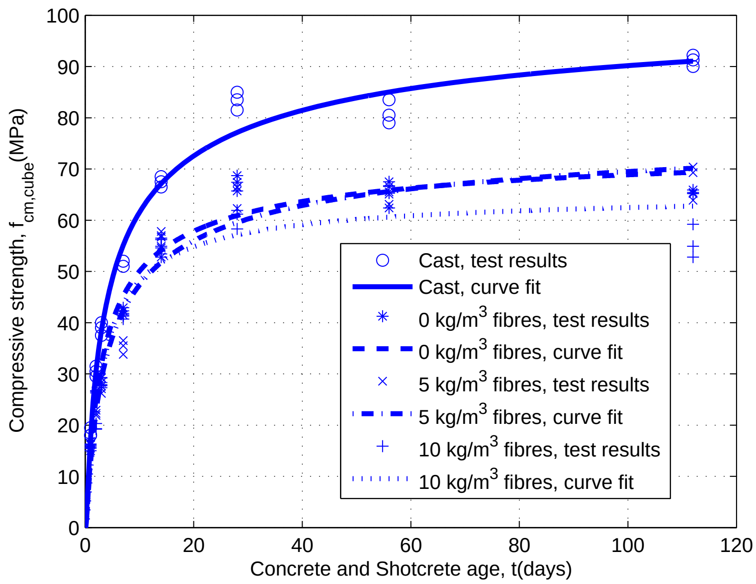


Figure 4.3. Compressive strengths from testing of shotcrete and cast reference samples. Additional results extend the age span up to 112 days (see Paper V).

4.3 Tensile strength

For the evaluation of shrinkage tests in Paper IV and V approximative, theoretically calculated tensile strengths f_{ctm} are used. The values are calculated from measured compressive strengths f_{cm} using relations given in Eurocode 2 (2004). The equation used is:

$$f_{ck} = \left(\frac{f_{ctm}}{0,3} \right)^{3/2} \tag{4.5}$$

where the compressive f_{ck} and tensile f_{ctm} strengths both shall be given in (MPa). It should be noted that the equation is intended for use with fully hardened cast concrete and that it may be less accurate when applied for very young concrete or shotcrete.

4.4 Bending tensile strength

Flexural crack strength testing has been done for shotcreted samples only, sawn from spray boxes and determined from ordinary flexural bending tests according to *Swedish Standard SS-EN 14488-3:2006* (SSI, 2006b). An example of a crack surface generated by a bending test is shown in Figure 4.4. Tiny parts of glass fibre residue are protruding from the failure surfaces of the shotcrete beam.

Figure 4.4. Glass fibre in failure surface of beam tested in bending.

Results for shotcreted beams with different glass fibre contents are presented in Paper V, for ages up to 28 days. As for the compressive strength tests these series were also continued with measurements at 56 and 112 days of age, resulting in the data presented in Figure 4.4. Also these fitted curves can be compared with those given in Paper V, but here it should be noted that the values obtained at 14 days have been excluded due to large deviation and possible uncertainties in the registered results. In this case Eqs. (4.6-4.8) gives, for shotcreted samples with 0 kg/m³ glass fibres as:

$$f_{\text{ctm,fl}} = 6,40\,\mathrm{e}^{-0,75/t^{0,67}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{4.6}$$

For shotcreted samples with 5 kg/m³ glass fibres:

$$f_{\text{ctm,fl}} = 7,24\,\mathrm{e}^{-0,82/t^{0,44}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{4.7}$$

For shotcreted samples with 10 kg/m³ glass fibres:

$$f_{\text{ctm,fl}} = 5,99\,\mathrm{e}^{-0,80/t^{0,99}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{4.8}$$

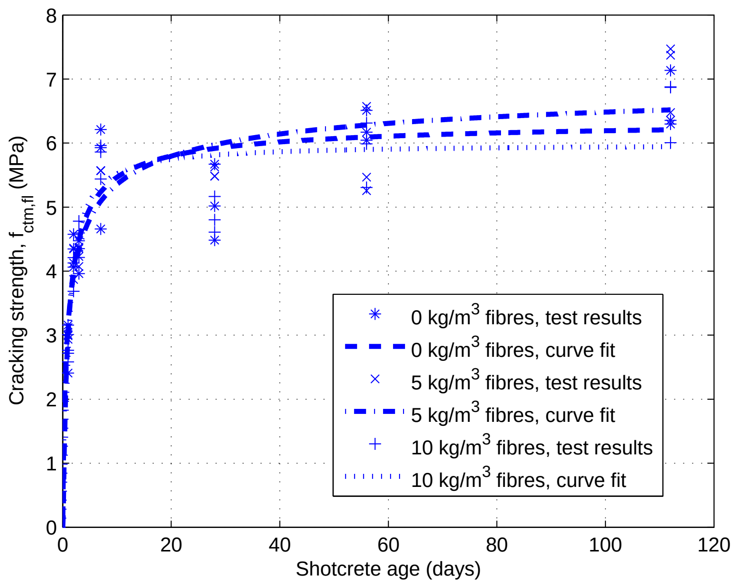


Figure 4.5. Flexural crack strengths from testing of shotcrete. Additional results extend the age span up to 112 days (see Paper V).

4.5 Elastic modulus

Elastic modulus can be estimated on basis of flexural tests according to the *Swedish Standard SS-EN 14488-3:2006* (SSI, 2006b). For the test results presented in Figure 4.5 the corresponding elastic modulus results are shown in Figure 4.6. Curves have also been fitted to these data points and for shotcreted samples with 0 kg/m^3 glass fibres the relation becomes:

$$E_{\mathrm{cm}} = 26{,}30\,\mathrm{e}^{-0{,}47/t^{0{,}59}} \quad \text{(GPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{4.9}$$

For shotcreted samples with 5 kg/m^3 glass fibres:

$$E_{\mathrm{cm}} = 28{,}56\,\mathrm{e}^{-0{,}67/t^{0{,}37}} \quad \text{(GPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{4.10}$$

For shotcreted samples with 10 kg/m^3 glass fibres:

$$E_{\mathrm{cm}} = 21{,}32\,\mathrm{e}^{-0{,}53/t^{2{,}01}} \quad \text{(GPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{4.11}$$

The recalculated test results and fitted curves underestimate the elastic modulus when compared to values calculated from the compressive strength tests shown in Figure 4.3, with up to 30-40%. This is partly due to possible inaccuracy in registration of deformation during the flexural tests with very small deflections of the test beams prior to cracking. The reason is the brittleness of the glass fibres used, in comparison to steel fibres for which the test method is more suited. However, the ultimate loads have been registered with great accuracy which also is the case for the flexural bending strengths given in Figure 4.5. It should be noted that due to this uncertainty in the registered deformations the evaluation of the test results in Papers IV-V were done based on elastic modulus values approximated from compressive strength test data. For approximation of elastic modulus from known compressive strength the Eurocode 2 (2004) recommends the relation:

$$E_{\mathrm{cm}} = 22\left(\frac{f_{\mathrm{cm}}}{10}\right)^{0{,}3} \tag{4.12}$$

where the compressive strength f_{cm} shall be given in (MPa) while E_{cm} shall be in (GPa). For comparison, results adjusted to comply with Eq. (4.12) and Figure 4.3 are given in Figure 4.6. The rescaled curves are based on the parameters given in Table 4.4.

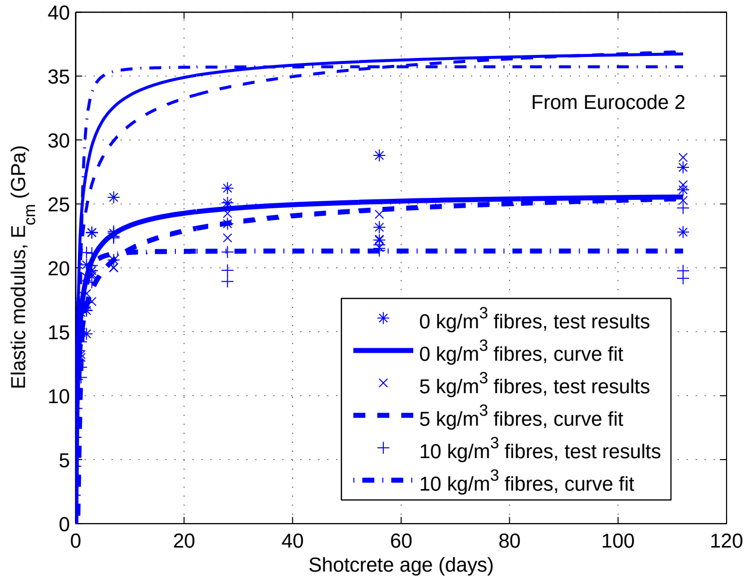


Figure 4.6. Elastic modulus for shotcrete. Calculated from the flexural crack strengths test results (Paper V). Compared to results calculated from compressive strength (Eurocode 2, 2004).

Table 4.4. Elastic modulus for shotcrete estimated from test results for flexural and bending strengths, respectively. With various contents of glass fibres.

Test no.	**Steel fibres (kg/m³)**	**Glass fibres (kg/m³)**	**E_{cm} (GPa) from flexural test**	**E_{cm} (GPa) from f_{cm}**	**Compressive strength (MPa)**
1	0	0	24,9	36,8	55,5 (69,4)
2	0	5 (6 mm)	25,8	36,9	56,1 (70,1)
3	0	10 (6 mm)	20,8	35,7	50,1 (62,7)
			See Figure 4.5 & Eqs.(4.9-11)	See Figure 4.3 & Eq.(4.13)	f_{cm}=0,8($f_{cm,cube}$)

4.6 Bond strength

One of the main properties for shotcrete used within the tunnelling sector is the bond strength, which has been studied in Papers I-III. The main three principles for bond strength testing are shown in Figure 4.7, where methods (a) and (b) are used today. The method described in (a) is the most frequently occurring but the shotcrete has to be hardened before the test is performed, which is usually done after 28 days. The second method (b) is to pull out steel discs mounted on rock surfaces prior to shotcreting and is e.g. described by O'Donnell and Tannant (1997). The method will only give an indirect measure of the bond strength between shotcrete and rock since the failure mode is a mix of bond loss and tensile failure. However, the method can be used with very young shotcrete. The third technique (c) is the basic principle that has been in focus in Papers I-III. In this case the direction of pull is reversed compared with the other two methods, making it possible to distribute the pull-out force over the core cross-section area, thus making a direct measurement of the bond stress possible, also for very young shotcrete.

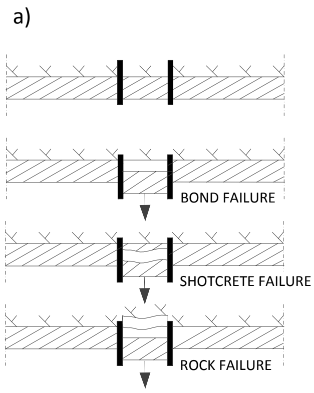


Figure 4.7. Methods for bond strength testing. Pull-out of drilled test cores (a), pull-out of shotcrete covered steel discs (b) and pull-out in the reversed direction of a substrate core (c). From Papers I-II.

The special boxes used for bond strength testing prior to shotcreting are shown in Figure 4.8, with nine cores in each. In Paper I the method for use with cast concrete is presented and Paper II presents the developed method for shotcrete in more detail. The results obtained in Paper I for cast concrete, with and without set accelerator, are compared with the results for accelerated shotcrete presented in Paper II, where tests with two different curing temperatures are included.

Figure 4.8. Special test boxes for bond strength tests.

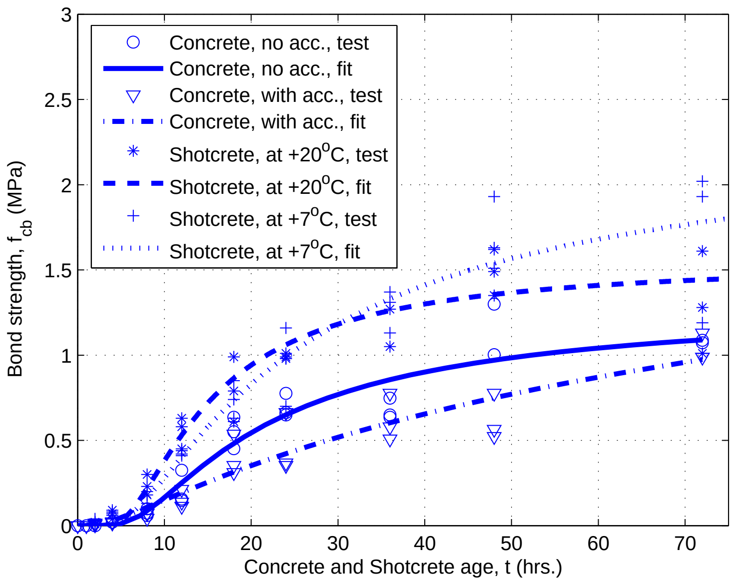


Figure 4.9. Bond strength vs. age for cast concrete with and without set accelerator (Paper I) and for shotcrete at +7°C and +20°C (Paper II). Test results and fitted curves.

4.7 Free shrinkage

The free shrinkage has been tested according to *Swedish Standard SS 137215* (SSI, 2000). Details about the production of test specimens are found in Paper V, for both cast and sprayed concrete together with results obtained for concrete and shotcrete ages up to 28 days. Results for shotcreted beams with different glass fibre contents are presented in Paper V, for ages up to 28 days. Also these test series were continued with measurements at 56 and 112 days of age, resulting in Figure 4.10. The curves fitted are valid from 7 days of concrete and shotcrete age and Eqs. (4.13-16) given below should be compared to the corresponding equations in Paper V, valid up to 28 days. For cast concrete samples is here:

$$\varepsilon_{sh} = 0,080\,\mathrm{e}^{-4,14/(t-7)^{0,42}} \quad \text{for} \quad 7 \le t \le 112 \text{ days} \tag{4.13}$$

For shotcreted samples with 0 kg/m³ glass fibres:

$$\varepsilon_{sh} = 0,085\,\mathrm{e}^{-4,22/(t-7)^{0,42}} \quad \text{for} \quad 7 \le t \le 112 \text{ days} \tag{4.14}$$

For shotcreted samples with 5 kg/m³ glass fibres:

$$\varepsilon_{sh} = 0,076\,\mathrm{e}^{-4,35/(t-7)^{0,50}} \quad \text{for} \quad 7 \le t \le 112 \text{ days} \tag{4.15}$$

For shotcreted samples with 10 kg/m³ glass fibres:

$$\varepsilon_{sh} = 0,083\,\mathrm{e}^{-4,33/(t-7)^{0,50}} \quad \text{for} \quad 7 \le t \le 112 \text{ days} \tag{4.16}$$

The measurement of free shrinkage was continued up to 365 days. The 365 days measurement deviates some from the measurements from 112 days, indicating either swelling of the test samples or measurement faults. The most important difference is that the cast sample shows the largest change and is no longer the specimen that has the lowest shrinkage. The sprayed samples are at the same strain level as registered at 112 days, were the 10 kg/m³ samples show the largest and 0 kg/m³ the lowest shrinkage. Due to the uncertainties in the results, also with reliable measurements between 112 and 365 days missing, the later results have been excluded from Figure 4.10. However, it should be noted the trend is that the cast concrete shows the largest change in shrinkage, also at 365 days.

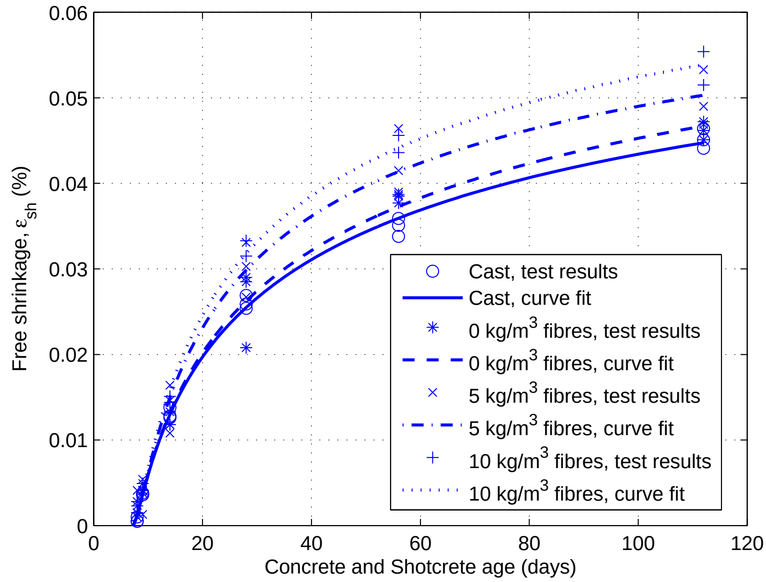


Figure 4.10. Free shrinkage from testing of shotcrete and cast reference samples, from 7 days of age. Additional results extend the age span up to 112 days (see Paper V).

4.8 Fully restrained shrinkage

Restrained shrinkage tests with ring specimens as shown in Figure 4.11 are presented in Paper IV. The results shown in Table 4.5 are a compilation of the study done by Holmgren and Ansell (2008 a-b) and Bryne and Ansell (2011). Observations up till approximately 800 days complement the table. In group 10 no visual cracks has developed, only micro cracks have been detected after 800 days.

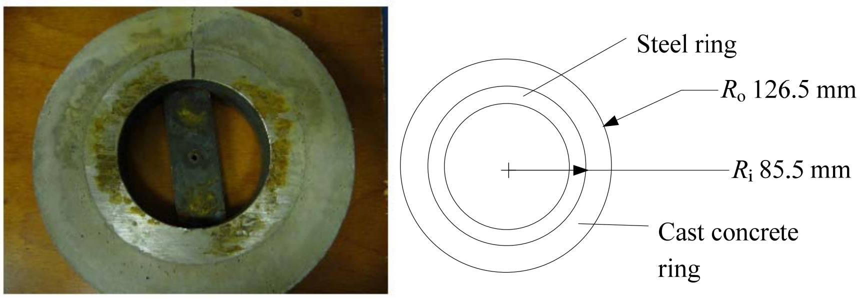


Figure 4.11. A concrete ring with outer radius R_o and an inner radius R_i is simply cast around an internal steel ring with a thickness of 28 mm. From Paper IV.

Table 4.5. Results from testing of ϕ253 mm concrete shrinkage rings (see Fig. 3) with various contents of fibre reinforcement. Number of rings with macro cracks and corresponding ages at cracking. Possible occurrence of micro cracks. From Paper IV.

Test no.	**No. spec.**	**Steel fibres (kg/m³)**	**Glass fibres (kg/m³)**	**Macro crack**		**Micro crack**	
				Number of rings cracked	**Age at cracking, days**	**Existence at 200 d.**	**Existence at 800 d.**
1 [1]	3	0	0	3	31-38	Irrelevant	Irrelevant
2 [1]	3	50	0	3	43-65	Irrelevant	Irrelevant
3 [1]	3	50	26 (6 mm)	0	-	No	Unknown
4 [1]	3	50	26 (12 mm)	0	-	Yes	Unknown
5 [2]	2	0	0	2	35-55	Irrelevant	Irrelevant
6 [2]	2	50	0	1	50	Irrelevant	Irrelevant
7 [2]	2	50	5	1	~800	Yes	Yes
8 [2]	2	50	10	1	~800	Yes	Yes
9 [2]	2	50	15	2	85	Yes	Yes
10 [2]	2	50	20	0	-	No	Yes

Results from [1] Ansell and Holmgren (2008b), [2] Bryne and Ansell (2011).

4.9 Partly restrained shrinkage

Restrained shrinkage tests are presented in Papers IV and V. In Paper IV both ring tests and the newly developed slab tests is reported, with only cast concrete in focus. These slab tests should be seen as a pilot test before the tests reported in Paper V, performed with sprayed concrete, i.e. shotcrete. The principles of the restrained slab test are shown in Figure 4.12. On top of the granite slab there is a plastic sheet which provides a de-bonded area and simulates the drainage mat. The spraying procedure of the test slabs is shown in Figure 4.13. A shotcreted granite slab, also equipped with the strain gauges connected with monitoring cables, is shown in Figure 4.14.

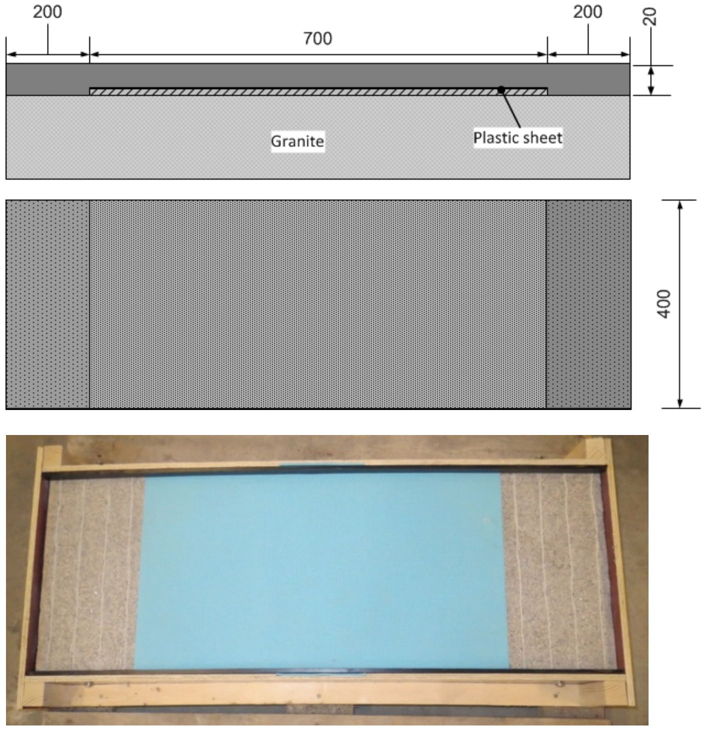


Figure 4.12. End-restrained shrinkage test sample. The de-bonded length is 700 mm.

Figure 4.13. Spraying of test slabs.

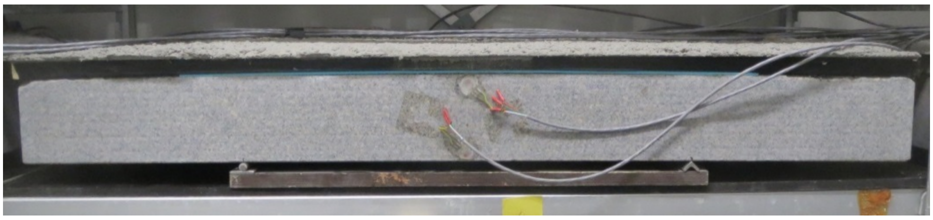


Figure 4.14. End-restrained specimen with strain gauges and cables.

In Paper V examples of results from testing of slabs number 1 and 6 are shown. In the following the results for all six tested slabs are given. The variation in thickness of the shotcreted layer of the test slabs are shown with 3D surface plots in Figure 4.15. Cracks have developed in five of the slabs, and in three of the cases the crack formation has developed in the middle of the slabs. In two cases cracks have developed in the vicinity of the ends. One slab (slab 6) is un-cracked, however it has been delaminated in one of the ends. The slab that did not crack had a glass fibre content of 10 kg/m^3. The profiles across and along the slabs are given in Figure 4.16, where also the average shotcrete thickness and crack profiles are shown. The measured strains for all six test slabs are given in Figure 4.17.

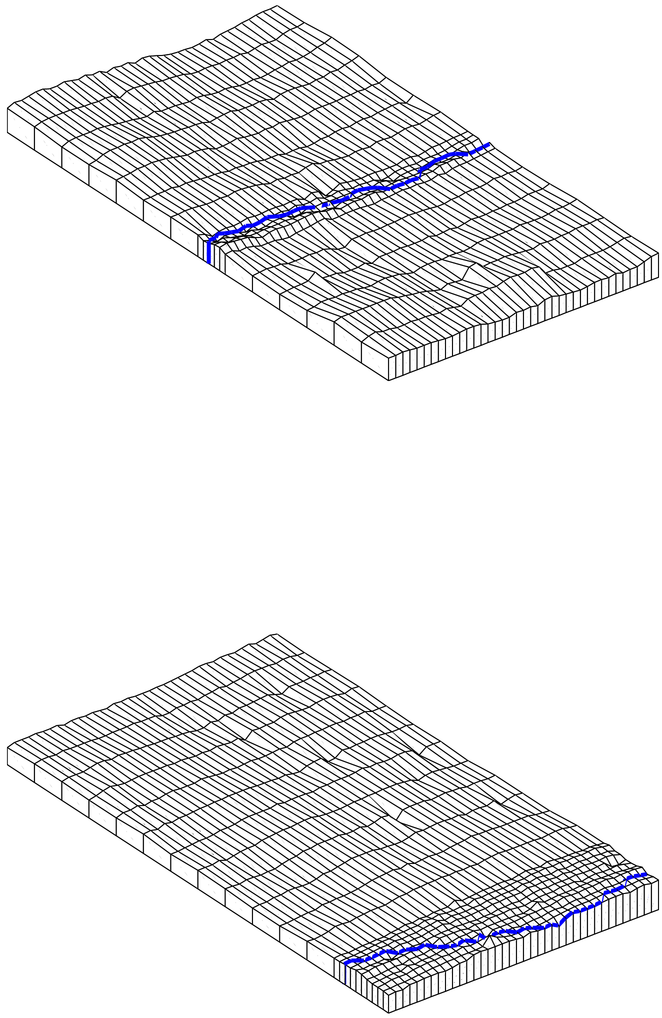


Figure 4.15a. Surface topology for test slabs 1 (top) and 2 (bottom). Cracks are marked with solid, blue lines. The basic horizontal measurement grid is 10×50 mm².

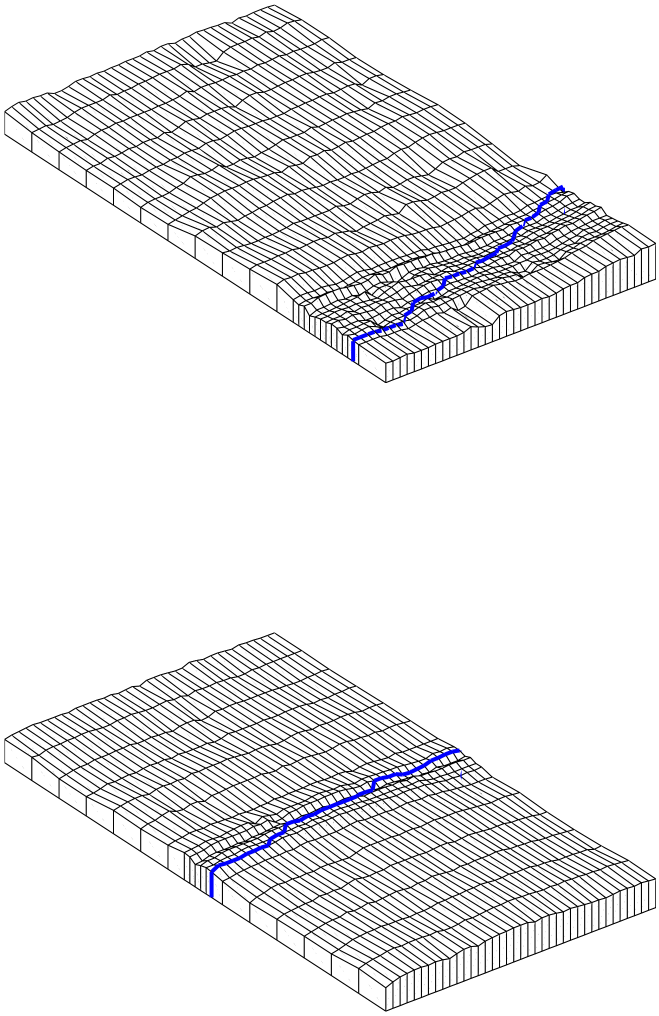


Figure 4.15b. Surface topology for test slabs 3 (top) and 4 (bottom). Cracks are marked with solid, blue lines. The basic horizontal measurement grid is 10×50 mm².

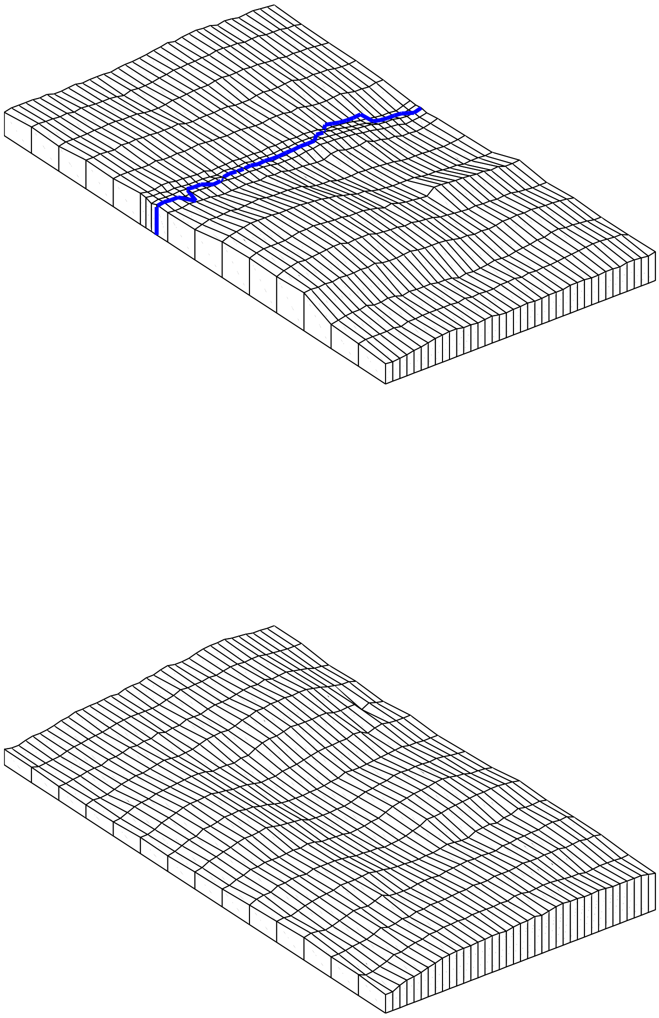
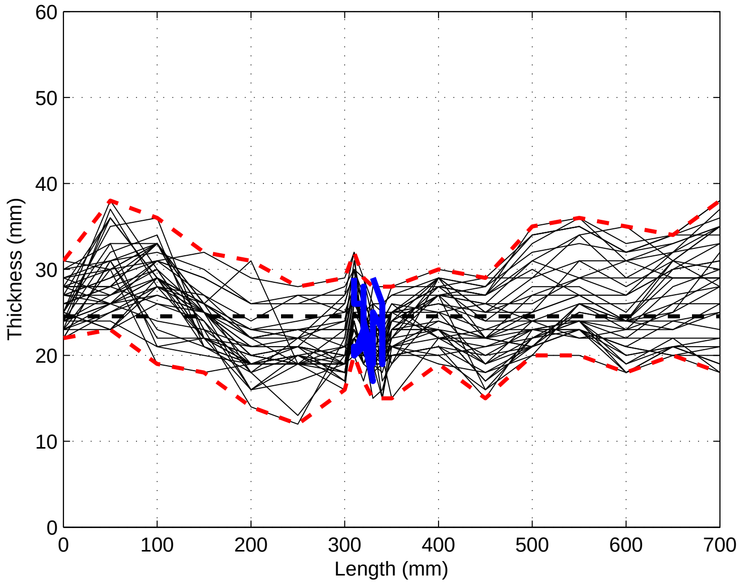


Figure 4.15c. Surface topology for test slabs 5 (top) and 6 (bottom). Cracks are marked with solid, blue lines. The basic horizontal measurement grid is 10×50 mm².



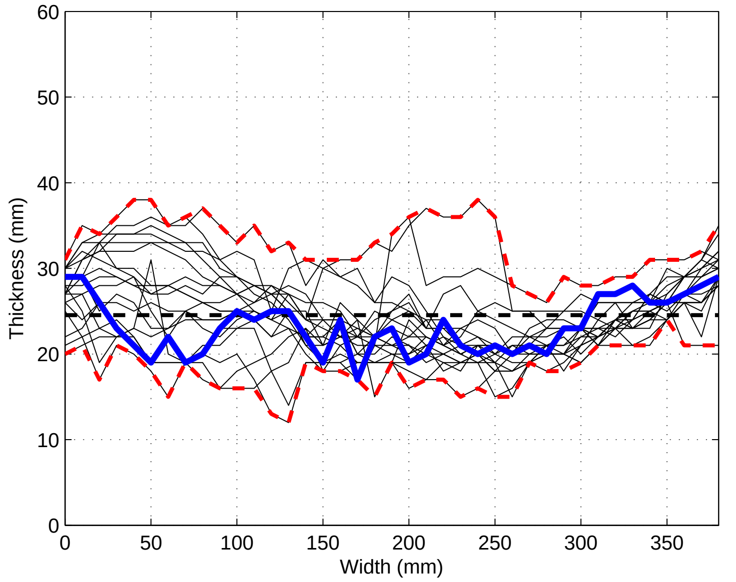


Figure 4.16a. Profiles for test slab 1 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.

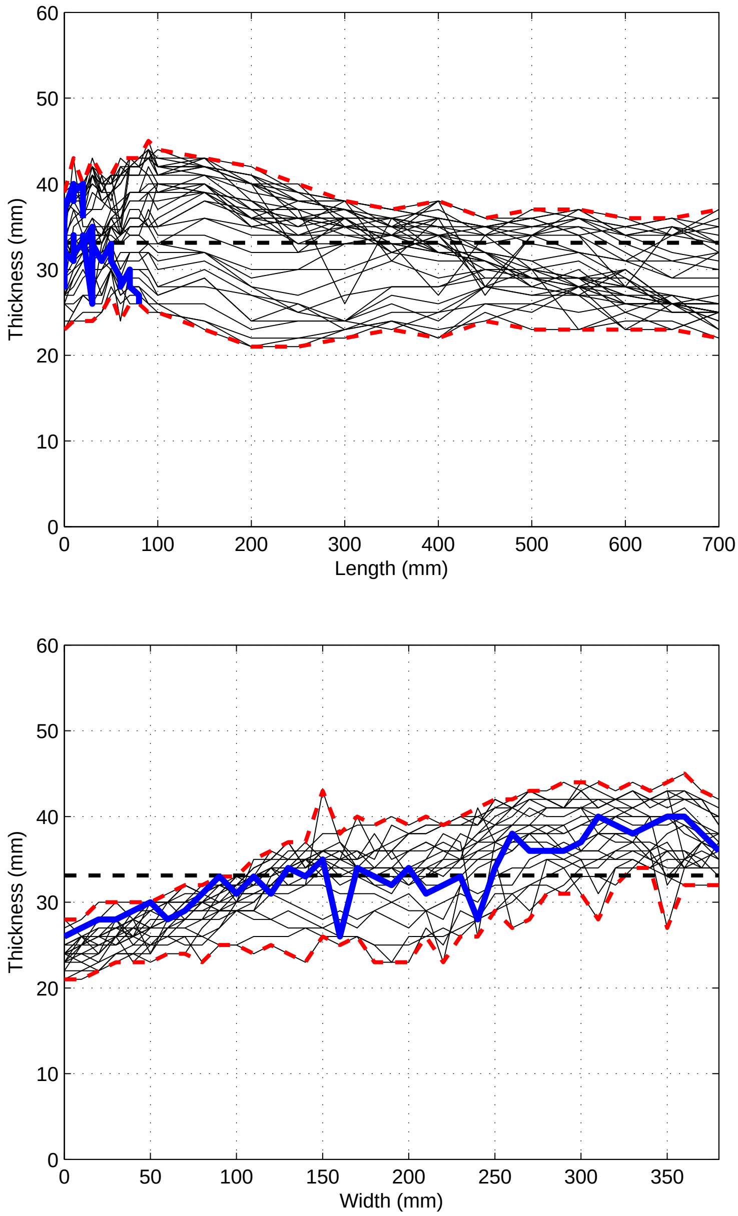


Figure 4.16b. Profiles for test slab 2 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.

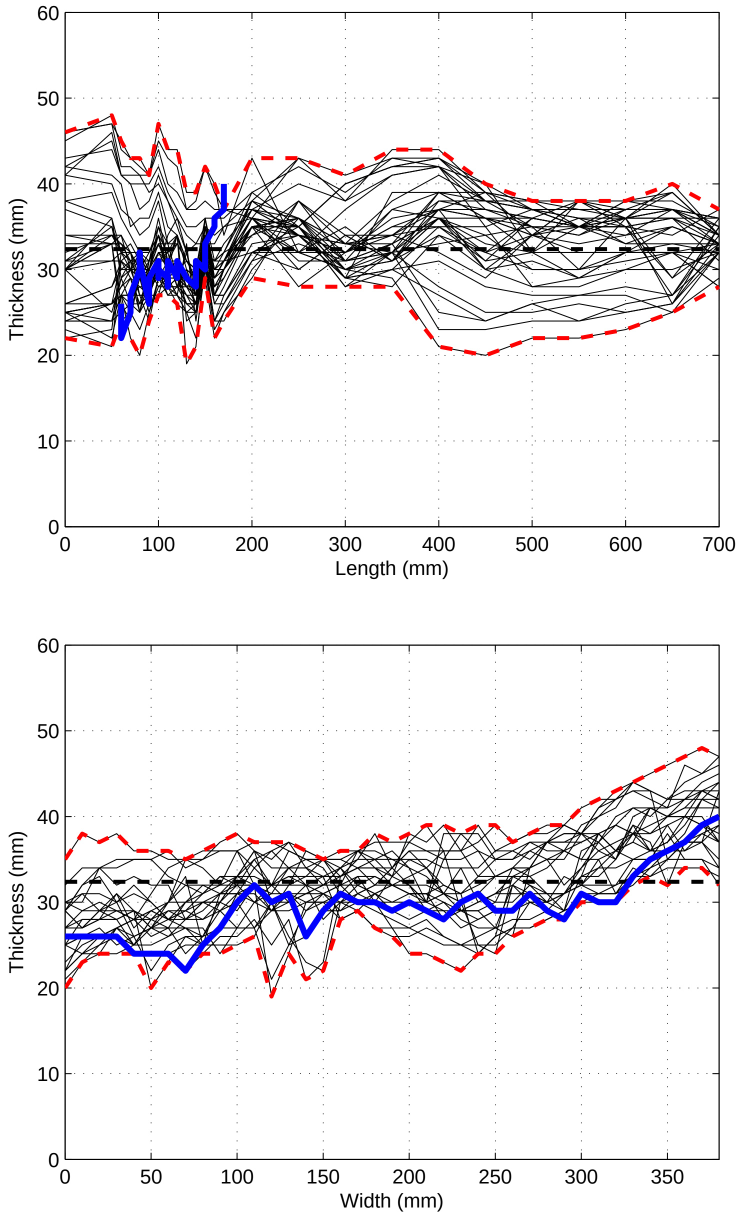
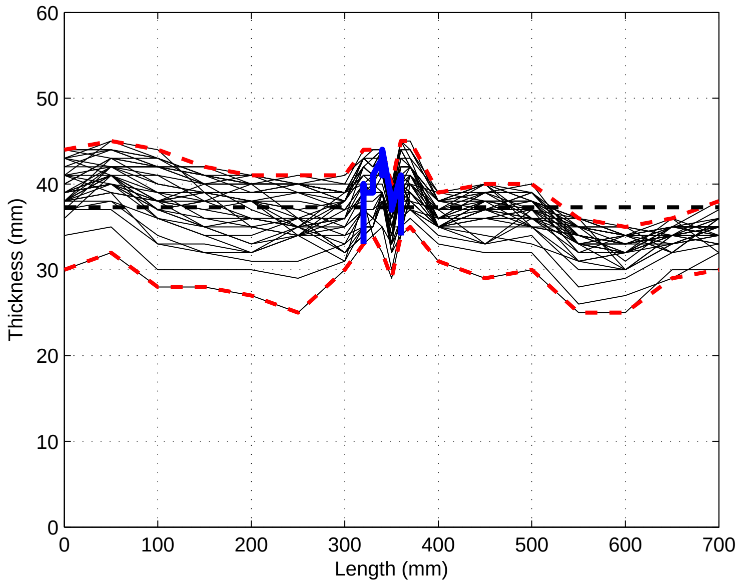


Figure 4.16c. Profiles for test slab 3 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.



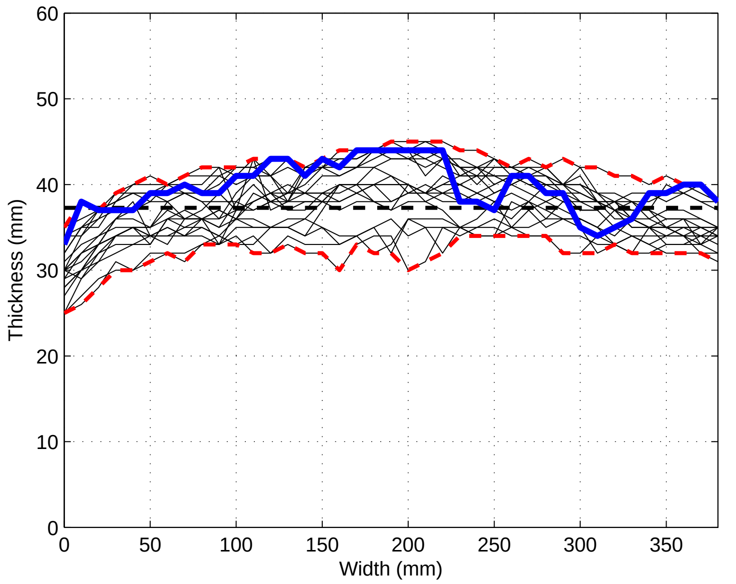


Figure 4.16d. Profiles for test slab 4 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.

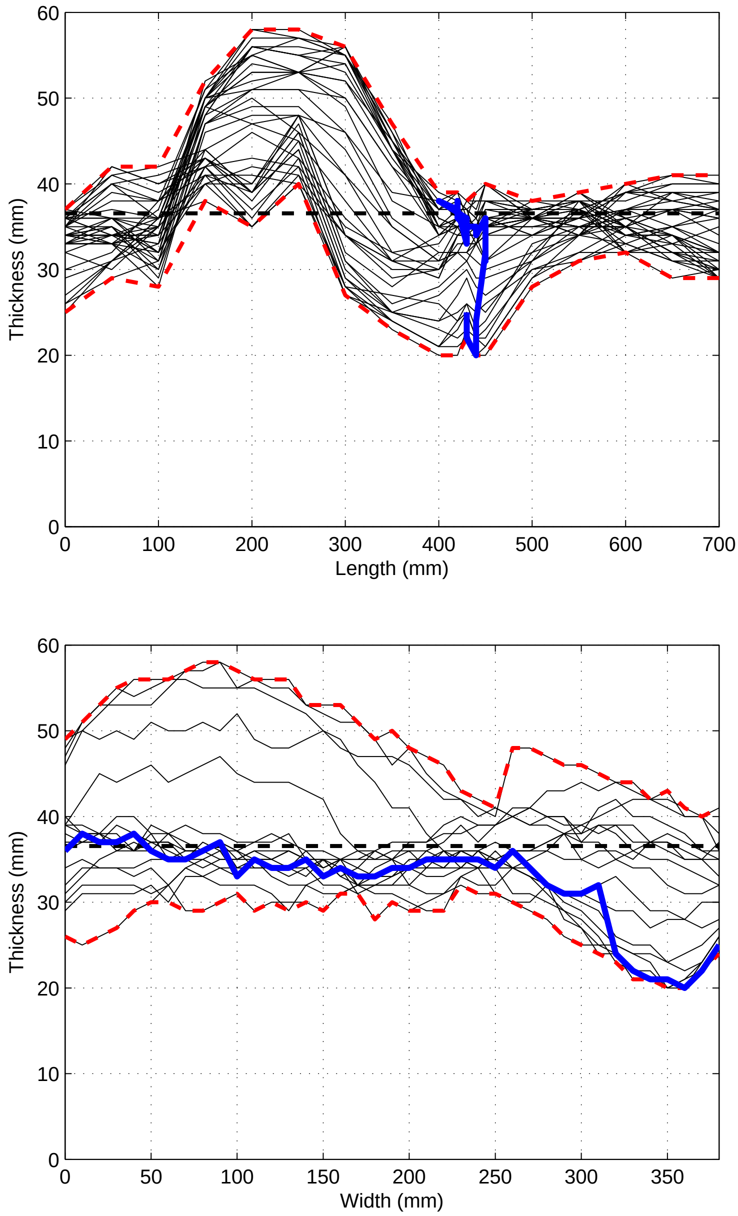
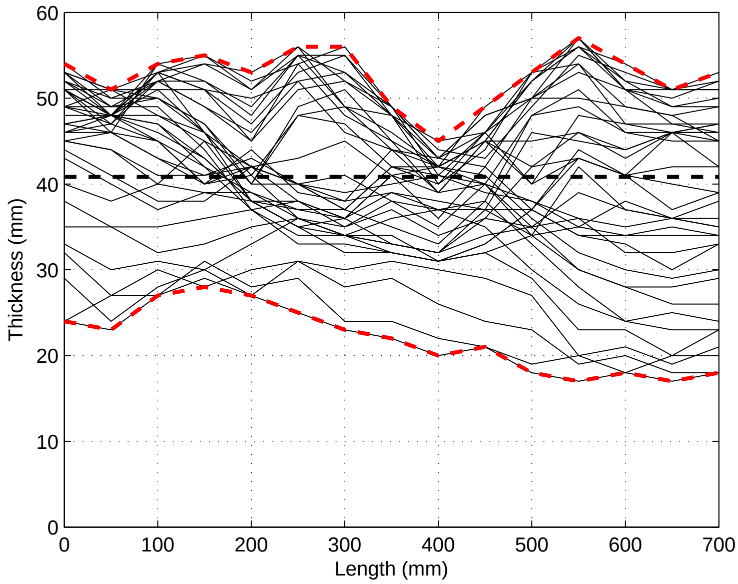


Figure 4.16e. Profiles for test slab 5 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.



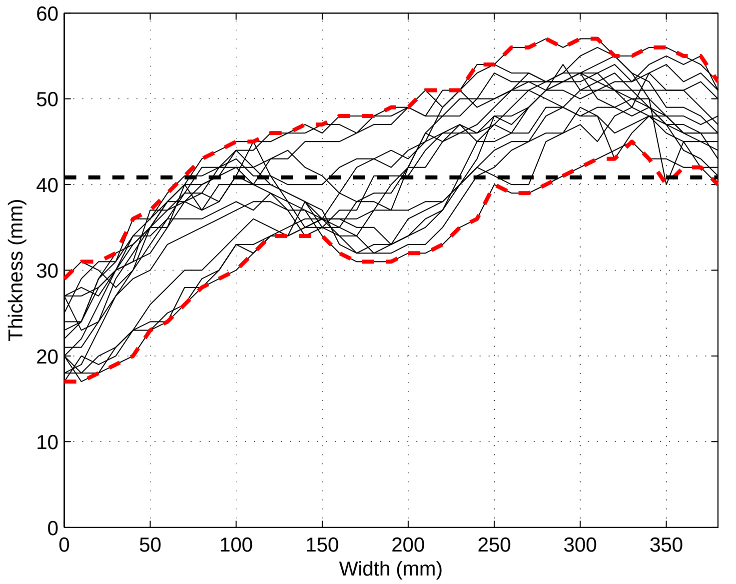


Figure 4.16f. Profiles for test slab 6 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.

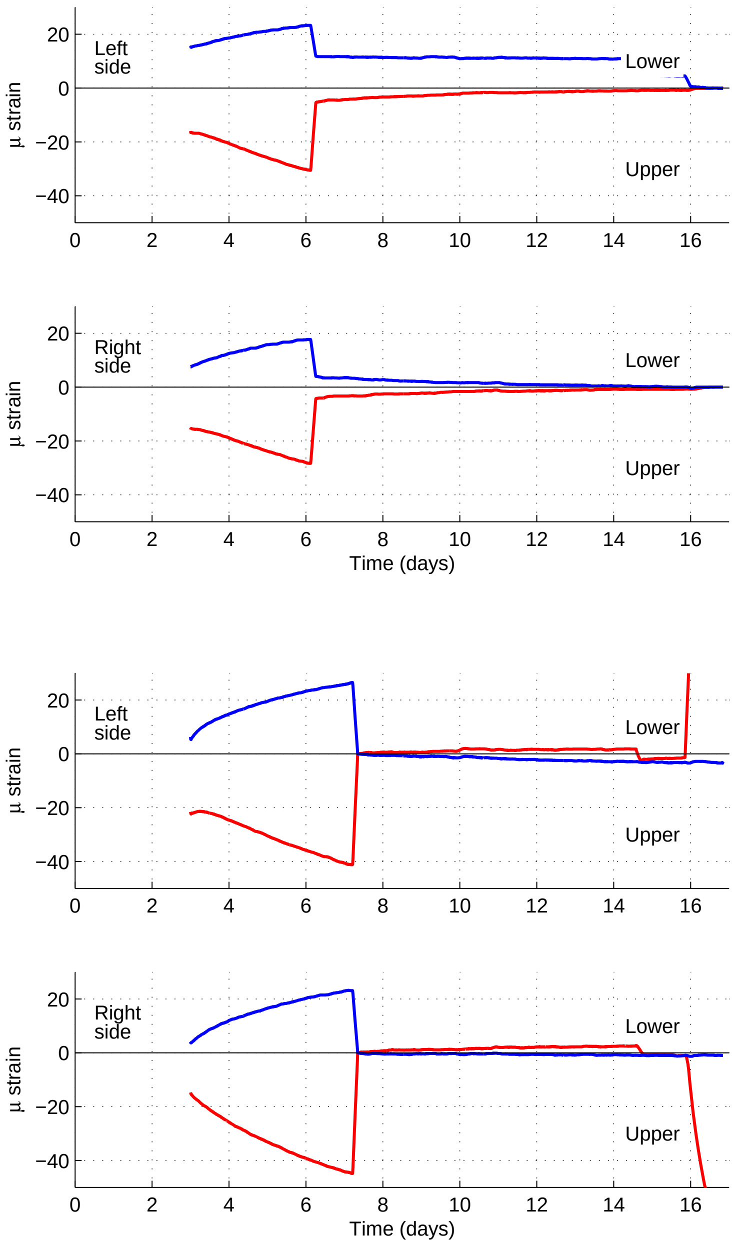


Figure 4.17a. Measured strains for test slab 1 (top) and slab 2 (bottom). From upper and lower strain gauges on left and right side of each slab.

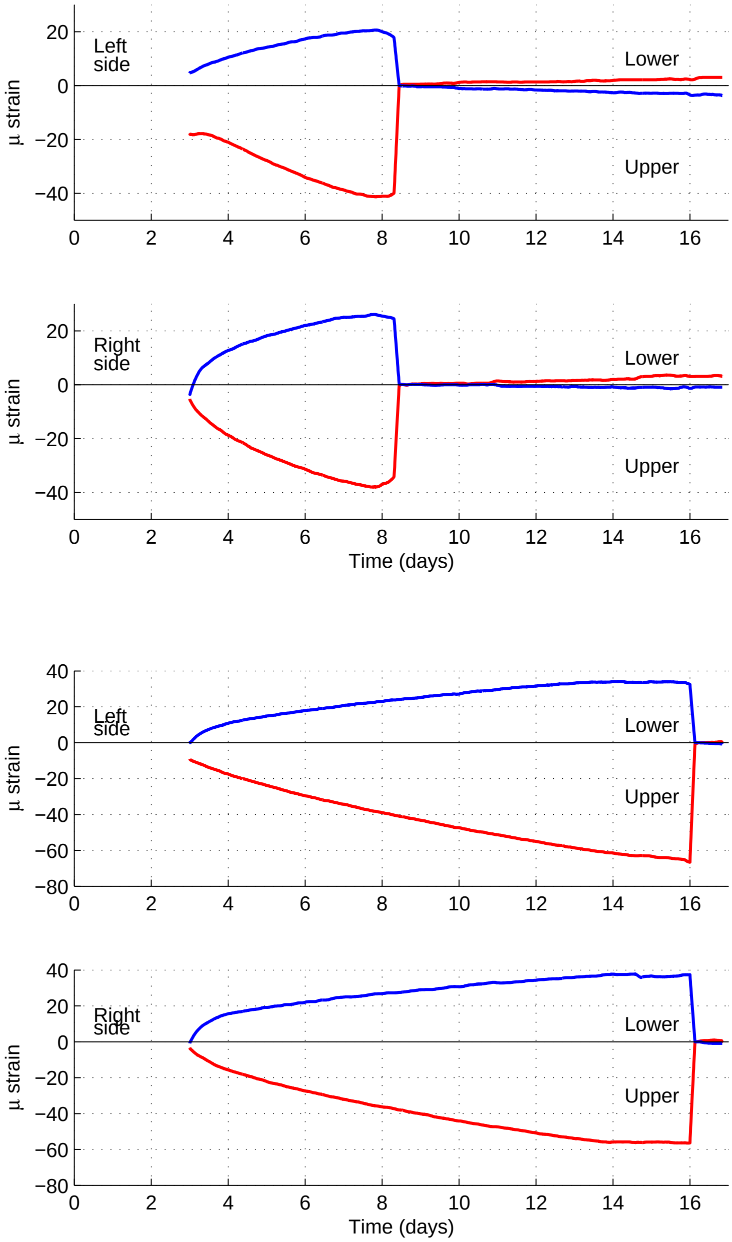


Figure 4.17b. Measured strains for test slab 3 (top) and slab 4 (bottom). From upper and lower strain gauges on left and right side of each slab.

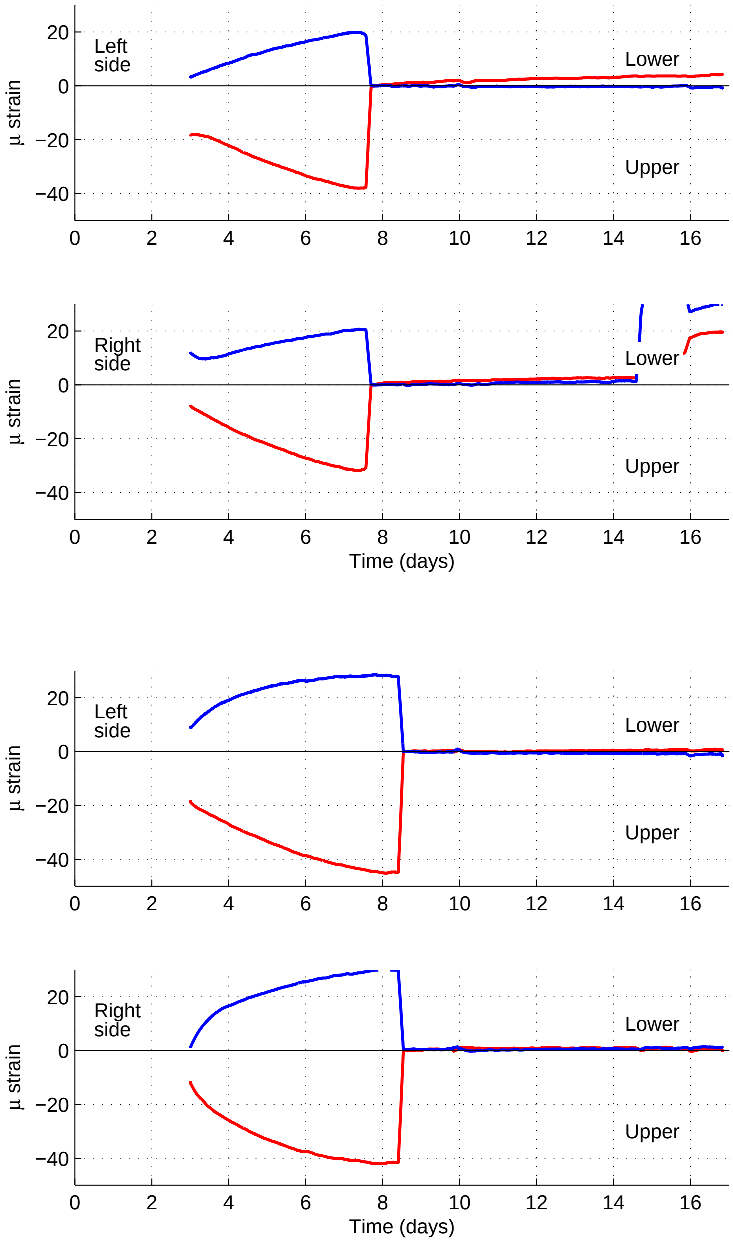


Figure 4.17c. Measured strains for test slab 5 (top) and slab 6 (bottom). From upper and lower strain gauges on left and right side of each slab.

4.10 Microstructure and chemistry of ITZ

The microstructure of the interfacial transition zone (ITZ) has been studied for the interaction between shotcrete and rock wall according to the bond strength testing. The test specimen has been prepared according to the description in Paper III. The main principle has been to stop the hydration process of the concrete that is remaining on the granite core directly after bond strength testing. This has been done with alcohol for at least 24 hours, see Paper III for more detailed information. SEM micrographs of the ITZ of shotcrete at different ages up till 24 hours for +7°C and +20°C at a magnification of 7000 times are presented in Figure 4.18. After 2 hours, the binding matrix mainly consists of very small ettringite crystals. The EDAX analysis shows an uneven chemical composition and areas rich in sulphate or aluminate could be detected. Some areas also contain magnesium from the set accelerator containing this element in addition to sulphate and aluminium. After 8 hours the gel (C-S-H) could be detected but no Portlandite. No individual ettringite crystals could be detected. The CaO/SiO_2 ratio is variable but comparatively high. The content of aluminate and sulphate is higher than in normal cement pastes. After 12 hours the cement matrix is denser due to further hydration. The CaO/SiO_2 ratio is variable but slightly lower than after 8 hours. After 24 hours the cement matrix is similar to that of ordinary cement paste. In most cases no ettringite can be detected, the only sign of the earlier ettringite is slightly higher values of sulphate and aluminate than in an ordinary paste with the same cement and w/c ratio. Also, the texture with hollow grains, typical of cement hydration, can be observed. At 24 hours it is possible to detect Portlandite (CaO) areas. The results from the EDAX analysis is shown in Table 4.6, showing the general trend of the chemical composition of the ITZ generated from the micrographs of a magnification of around 7000 times.

Table 4.6. Typical oxide compostions according to main chemical compound given in weight percent.Two conducted analysis for each time except for 72 h and reference sample.

Time	2h	2h	8h	8h	12h	12h	24h	24h	72h	Ref
MgO	1,6	10,3	1,5	0,8	1,1	1,4	1,1	0,8	1,2	----
Al_2O_3	5,5	13,9	8,1	4,0	7,4	2,7	5,3	6,2	6,4	3,5
SiO_2	35,8	34,1	29,1	37,0	31,5	29,6	36,2	36,3	30,9	34,5
K_2O	0,8	0,8	1,1	0,3	0,9	0,2	0,3	0,2	1,1	0,8
SO_3	3,1	4,9	6,7	4,7	5,8	1,9	4,5	4,3	5,3	3,8
CaO	49,2	25,2	53,5	51,1	53,4	62,4	52,6	52,3	50,2	53,8
Fe_2O_3	3,9	10,8	----	2,1	----	1,7	----	----	5,0	3,2

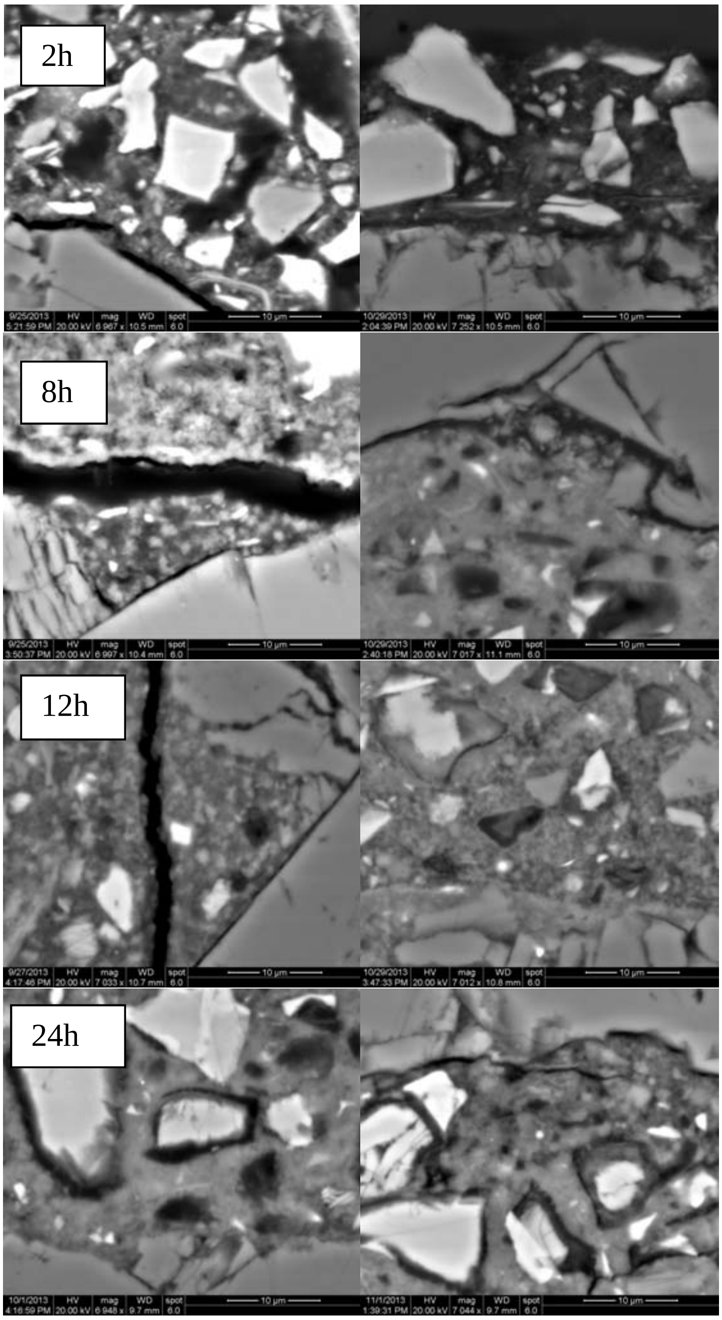


Figure 4.18 Micrographs of ITZ. Samples at +7°C (left) and 20°C (right). Magnification 7k.

5. Discussion

In the following the main parts of the work will be discussed and commented, also with a summary of the contents in Papers I-V. Focus is on bond strength, restrained shrinkage and the microstructural situation in the interfacial transition zone (ITZ) between shotcrete and hard granite rock. Results from bond strength testing are given in section 4.6 and Papers I-II, from the microstructural investigations in section 4.10 and Paper III while the results from shrinkage testing are given in sections 4.7–4.9 and Papers IV-V. The results for density and slump, compressive strength, tensile strength, flexural strength and elastic modulus summarized in sections 4.7–4.9 are commented where appropriate.

5.1 Bond strength

Bond strength tests were performed on both cast concrete and shotcrete within a time span of 2–72 hours. According to the different methods for compaction of the cast and the sprayed samples caution has to be taken when comparing the results. As shown in Figure 4.9 the sprayed samples show slightly higher values after 72 hours. Including all values it can be seen that the lowest for all tests, both cast and sprayed, is around 1 MPa. For the bond strength of cast concrete shown in Figure 4.9, it is obvious that samples with no accelerator develops faster than without accelerator, up to around 8 hours.

In Figure 5.1 the relative compressive and bond strength for cast concrete and shotcrete is given, at temperatures +20˚C and +7˚C respectively, as presented in Paper II. A comparison between material age and the rate of strength growth is made, and it can be seen that there is a shift at around 20 hours where shotcrete shows a faster compressive strength development at +20°C than at +7°C compared with cast concrete. However, the relative bond strength development by time is faster at +20°C than at +7°C. When studying the compressive strength results in Figures 4.2–4.3 it is obvious that ordinary cast concrete reaches significant higher values compared with shotcrete, both in the short time perspective, i.e. 3 days, as well as for longer times.

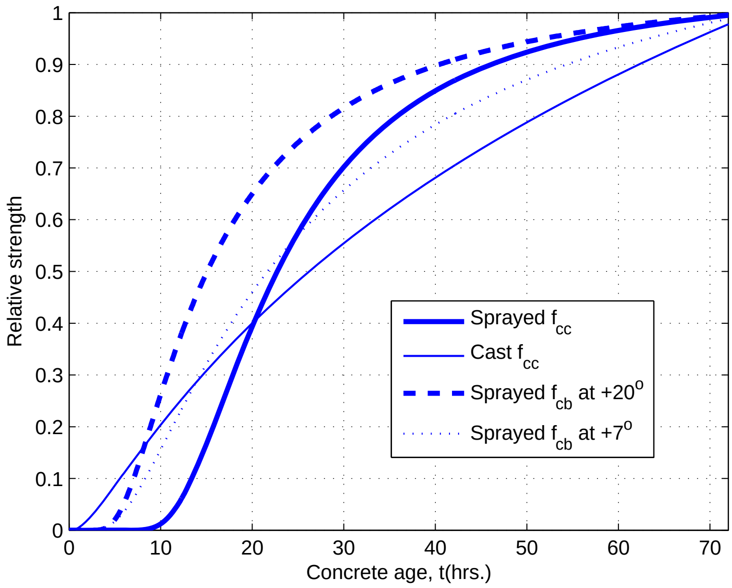
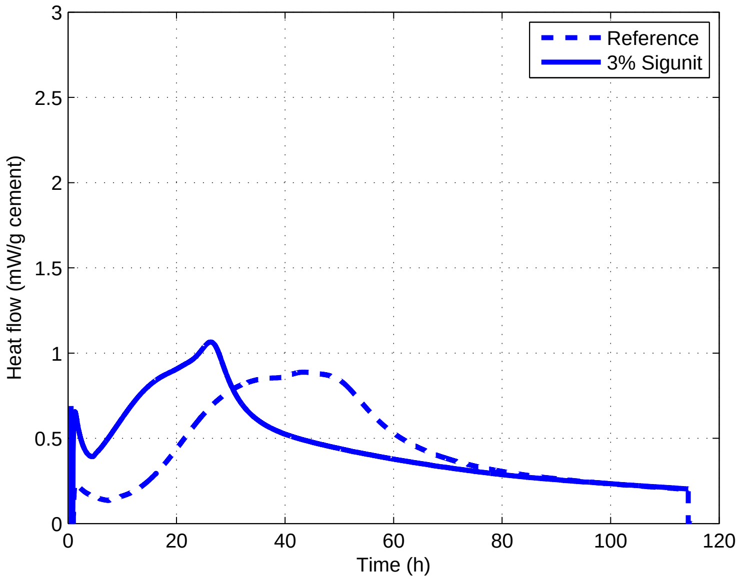


Figure 5.1. Relative strength vs. concrete age of compressive strength for cast and sprayed at +20°C, and bond strength for sprayed concrete at +20°C and +7°C, respectively. From Paper II.

Figure 5.2 is shown in Paper III and summarizes the results from the calorimetric study done on a cement mortar with a mix equivalent to the recipe in Table 4.1, but with only sand as aggregate. The speed of hydration has been analyzed by isothermal calorimetry (Figure 5.2) at both +8 and +20 °C. The results show that the acceleration period for the mix starts after around 3–4 hours at +20 °C and after around 6 hours at +8 °C. The set-accelerator (Sigunit) is accelerating the reaction compared with normal cement hydration. This was also found in an earlier work, with other set accelerators retarding the cement hydration (Lagerblad et al., 2006). This means that up to 5–6 hours the strength of the paste is mainly given by the ettringite network given by the set accelerator.



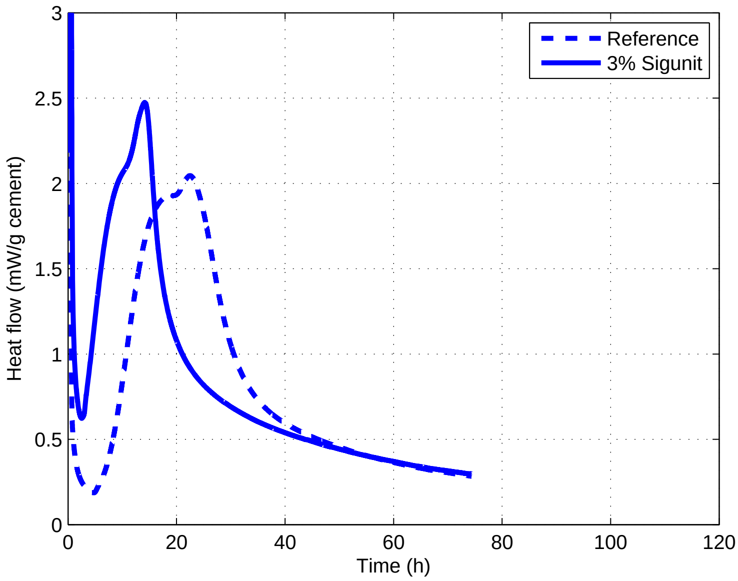


Figure 5.2. Energy release measured by isothermal calorimetry at two temperatures, +8°C (top) and +20°C (bottom), from Paper III.

a) 8 hrs.

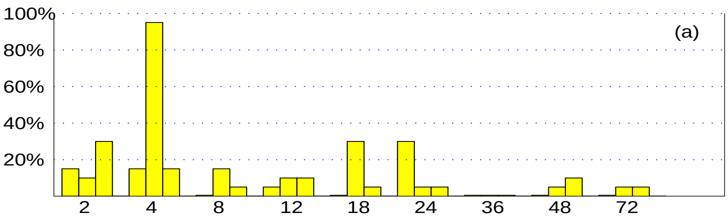
b) 36 hrs.

c) 72 hrs.

d) 8 hrs.

e) 36 hrs.

f) 72 hrs.



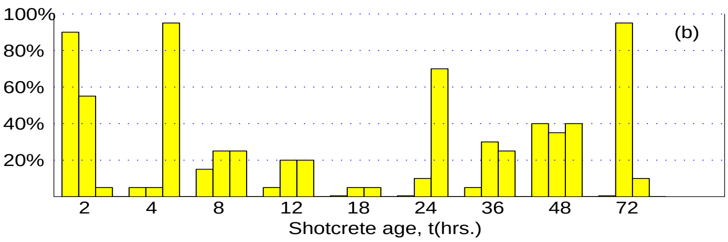


Figure 5.3. Typical failure modes at different temperatures and ages. Specimen (a)-(c) tested at +7°C and (d)-(f) at +20°C. Diagrams showing ratio of remaining shotcrete area on the rock interface after testing, at +20°C (a) and +7°C (b), from Paper II.

In Figure 4.9 the bond strength development in the pull-out test (from Paper I and II) is shown. At both +7 and +20°C the bond strength is low during the first hours which coincide with the hydration of the cement and strength gain of the shotcrete. In the beginning the strength is given by the ettringite matrix, resulting in a weak bond and it can be seen that it takes between 10 and 20 hours to get a proper bond strength. The pull out test shows that the strength growth at +7 °C starts somewhat later than at +20 °C but that the strength with time becomes higher. Thus, with a high quality shotcrete on a good surface the bond strength can be related to the strength gain and the texture of the concrete. The strength of the bond is dependent on the homogeneity of the shotcrete which in turn depends on the equipment and the skill of the nozzleman. It is also related to the texture and the conditions at the rock.

The adhesion phenomena is the sum of a number of mechanical, physical, and chemical overlap which influence each other. The wettability, chemical bonding and weak boundary layer have been postulated to describe the mechanism of adhesion in status of adsorption/surface reaction. Bond strength of cast concrete at +20°C, with and without set accelerator (Paper I) and shotcrete at both +20°C and +7°C (Paper II) has been studied, with almost the same concrete composition as given in Table 4.1. The values at 72 hours show some scattering but are within 1 and 2 MPa, while the cast samples show lower values, around 1 MPa. No compression tests have been done at +7°C but, as shown in Paper II, tests on the same shotcrete were performed at +20°C and these results were also used for recalculation into curves adjusted to represent compressive strength growth at +7°C. The latter are obtained by using the maturity function (the TT-method) in the form given by Byfors (1980). The compression strength development is depressed at lower temperatures and Figure 5.1 here shows the relative strength vs. concrete age in compression for cast and sprayed at +20°C, and in bond for sprayed concrete at +20°C and +7°C, respectively, as originally given in Paper II. For comparison, the same results for cast concrete are also presented. The compressive strength of the cast concrete develops faster until 20 hours, after that the strength increase for shotcrete is faster. It can be seen in Figure 5.2 that the hydration processes for the reference, with no accelerator, are slower than for samples with the accelerator, so that after 20 hours they become in line with the values in Figure 5.1. The development of the bond strength for the sprayed concrete in Figure 5.1 is faster at +20°C compared with +7°C, which seems to be in line with the results of the calorimetric measurements presented in Figure 5.2. However, it should be noted that the calorimetric data in Figure 5.2 represents a minor study.

Some typical failure modes from bond strength testing at different temperatures and ages are shown in Figure 5.3. They were defined through estimation of the ratio of material remaining on the rock core surface after testing to the total area. A low ratio thus corresponds to a pure bond failure while the opposite represents a tensile failure, with remaining shotcrete material covering the entire surface of the test core. Pure delamination failure modes, i.e. tensile failures, appear already at 36 hours at +20°C. Figure 5.3 also presents the distribution of failure modes for temperatures +20°C (a) and +7°C (b), respectively. There is a higher frequency of material tensile failures at +7°C compared with +20°C. A more detailed discussion is given in Paper II.

5.2 Interfacial transition zone

The microscopy study of the interface between shotcrete and hard rock shows a difference in density between the ITZ and at sections some millimeters from the rock wall, as shown in Figure 5.4 where the fluorescent impregnated thin sections reveal the porosity. In thin sections it is possible to observe a larger area than in SEM and here this shows a better packing of the aggregate grain in the concrete than at the ITZ. It is also possible to observe that the cement paste is denser in the concrete than at the ITZ. This is more clearly shown in the inset detail photos taken at a larger magnification.

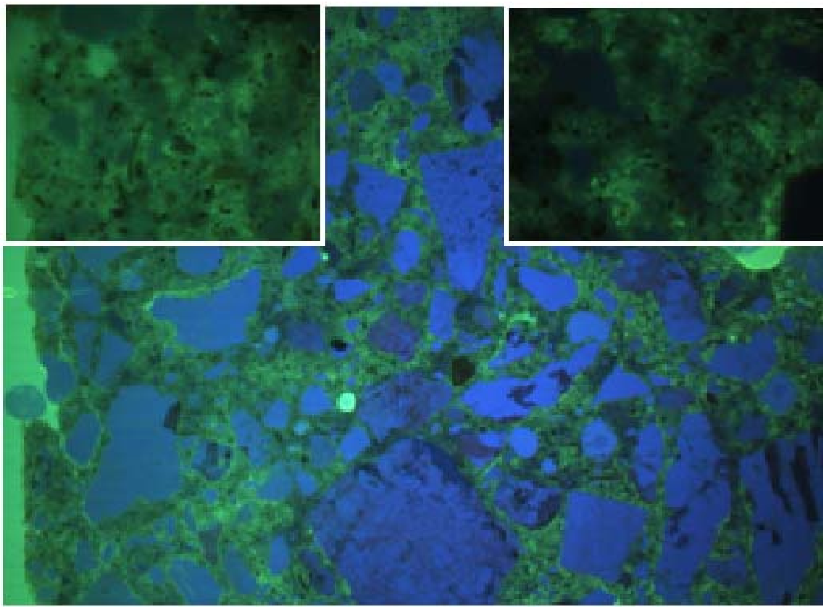


Figure 5.4. Thin ground sample studied in light microscope of ITZ. The side of the large photograph is 6.7 mm, and the two minor are 0.43 mm respectively. All SEM micrographs are taken within a range of 100 µm from the surface. From Paper III.

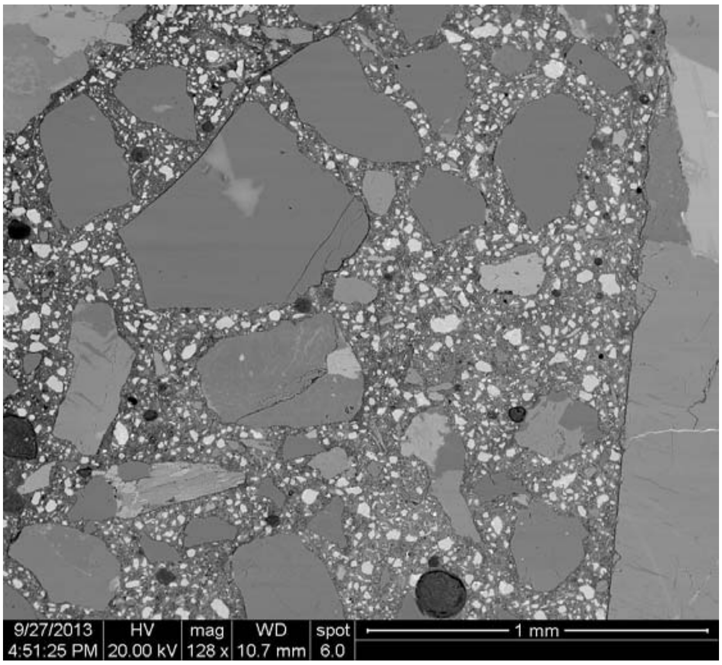


Figure 5.5. Micrographs of ITZ at 12 h, +7°C. Magnification is around 130 times. A darker or more porous structure in the left part of the micrograph. The granite core is situated to the right. From Paper III.

In Figure 4.18 SEM micrographs of the ITZ of shotcrete at different ages up till 24 hours for +7°C and +20°C at a magnification of 7000 times are presented. The binding matrix mainly consists of very small ettringite crystals after 2 hours. Presumably the texture was more homogeneous before drying. Uneven chemical composition and areas rich in sulphate or aluminate could be detected by the EDAX analysis. It was also possible to detect "paste" rich in silica, presumably restite of partly dissolved silica fume (see Paper III). Magnesium oxide, due to the set accelerator which contains this element in addition to sulphate and aluminium, was detected in some areas. After 8 hours the gel (C-S-H) could be detected, but no Portlandite. The cement paste is now more homogeneous and the shrinkage is less. This indicates that the cement paste now has gained some strength. No individual ettringite crystals could be detected, presumably due to the small grain size. The CaO/SiO_2 ratio is variable but comparatively high. The content of aluminate and sulphate is higher than in normal cement pastes. This indicates that the cement paste, due to that proper cement hydration develops from the earlier ettringite network. Hollow grains from small, totally dissolved cement particles can be observed which is typical for cement hydration, see Kjellsen and Lagerblad

(2007). After 12 hours the CaO/SiO_2 ratio is variable but slightly lower than after 8 hours and the cement matrix is denser due to further hydration. After 24 hours the cement matrix is similar to that of ordinary cement paste. In most cases no ettringite can be detected, the only sign of the earlier ettringite is slightly higher values of sulphate and aluminate than in an ordinary paste with the same cement and w/c ratio. Also, the texture with hollow grains, typical of cement hydration, can be observed. At 24 hours it is possible to detect portlandite (CaO) areas. The texture of the ITZ shows small gaps between rock and shotcrete and this is probably due to drying shrinkage. No chemical interaction between the cement paste and rock can be observed. The degree of packing of the cement particles is slightly lower at the contact area than further into the concrete.

The results from the EDAX analysis are shown in Table 4.6, with the general trend of the chemical composition of the ITZ generated from the micrographs of a magnification of around 7000 times. The EDAX study gives some general picture of the chemical map in the ITZ. To get a more precise picture, more surface sensitive methods than SEM have to be applied, e.g. x-ray photoelectron spectroscopy (XPS). It is also possible to study the surface energy situation according to the Wilhemy method or Inverse gas chromatograph (IGC). Table 4.6 gives an interesting distribution of the elemental combinations that roughly can be divided into three main groups of chemical structures, namely: sulphur rich compounds or agglomerates which can be lead to gypsum in the cement or undispersed set accelerator; cement paste with enriched signals of ettringite leading to secondary cement hydrates that grows from an ettringite primarily established structure created at the dispersion of set accelerator; ordinary C-S-H structures that emanate from sites were no mixing of set accelerator has occurred. For shotcrete at +7°C it is obvious that the structure from the beginning is an ettringite rich structure and already after 8 hours the C-S-H structure grows from the ettringite structure, which in Table 4.6 corresponds to cement paste with a lowering in sulphur content compared to enriched sulphur. It can also be seen that there is a huge variance in the composition between ettringite rich areas and C-S-H rich areas certainly due to insufficient dispersion of the alkali-free set accelerator. This can be lead to the signal of C-S-H content still after 24 hours. Traces of Portlandite can be seen already at 12 hours in samples of +20°C compared with observation at 24 hours in samples of +7°C. CaO shows already at 8 hours a lower variance for +20°C compared with +7°C, in a general overview.

5.3 Shrinkage

According to Figure 4.10, which shows free shrinkage of the fitted data until 112 days, the cast concrete has the lowest shrinkage and shotcrete with increasing fibre content show gradually higher values, both represented by fitted curves with a similar form. Comparing these results of glass fibres with Ramakrishnan (1985) the results are a bit low, however, in the latter case steel fibres were used. For comparison it should be noted that Carlswärd (2006) reported free shrinkage mean values, for steel fibres of a content of 20-40 kg/m^3, up to around 0,02-0,25‰ after 4–7 days.

Carlswärd also reported restrained shrinkage tests, done in parallel with the free shrinkage tests, with the time to cracking and crack width reported for steel and plastic fibres, with up to 7 days until cracking. Glass fibres delay the crack initiation at restrained shrinkage of ordinary cast concrete, as reported by Swamy and Stvarides (1979), which here certainly is the case for the ring tests, as reported in Paper IV. When comparing the results from the ring tests with those from the slab tests it is obvious that the long-time un-cracked behaviour obtained for the glass fibre specimens of the ring tests was not clearly repeated in the slab tests.
One important thing to remember when comparing the free shrinkage tests with the restrained slab tests is the distinct difference geometrical forms of the specimens. The free shrinkage tests were done using standardized specimens with dimensions 100×100×400 mm^3, but the slab test specimens had a varying height and a base area of 380×700 mm^2. Also, the geometrical shape of the ring test specimens has to be remembered as well.

Table 5.1. Results from strain measurements for all shotcrete mixes.

Test slab no.	1	2	3	4	5	6
Fibre content (kg/m^3)	0	0	5	5	10	10
Mean layer thickness (mm)	25	33	32	37	37	41
Minimum thickness (mm)	17	26	22	34	20	17
Time to failure (days)	6	7	8	16	7	8
Failure type	crack	crack	crack	crack	crack	bond
ε_U (µstrain)	-25	-43	-40	-66	-25	-44
ε_L (µstrain)	13	25	23	33	21	29

In Table 5.1 the results from the sprayed slab tests are summarized. A comparison of the different profiles in Figures 4.15–4.17 shows that it is obvious that the accuracy of the new method depends on the thickness variation of the shotcrete layer, i.e. the slab. The cracks pass the minimum thickness profiles in all the cracked specimens where, most certainly, the initiation of the cracks took place. It is also clear that the delamination failure at one of the anchorage areas seen in slab 6 is caused by an oversized shotcrete thickness. The test setup is based on a thickness of 20 mm, which is exceeded in all slabs. The thickness condition is very robust and minor spraying equipment should be used in future testing. The degree of restraint described as the ratio between real and free shrinkage is calculated in both Paper IV and V. In Paper V it is declared that the measured restraint was found to be larger for a specimen with a thinner shotcrete layer. This is coherent with the above discussion about the shotcrete layer thickness.

Figure 5.6. Crack formation in slab no 2 showing large aggregate impact pattern.

The photo in Figure 5.6 shows the crack formation at a part of slab 2, see also Figure 4.15 (a). It is obvious that the crack is going through the thinnest local points created of the impact of large aggregates, here with a maximum set to d_{max}= 8 mm. Maybe a smaller d_{max} should be used in future spraying but this will of course also aggravate the shrinkage. However, this is certainly a possible cause for cracking at sections other than at the middle of the slab, e.g. with cracks developed at the end of the slabs. This phenomenon may even be a source of cracking in real shotcrete tunnel profiles, for cases where a thin layer of shotcrete has been sprayed.

The flexural strength, i.e. the crack strength, which is summarized in Figure 4.5, shows a behaviour of the fitted curves that is quite different compared with the expressions given for a shorter time span in Paper V. This is also the case for the elastic modulus results shown in Figure 4.6. One interesting detail about Figure 4.6 is also the comparison with modulus values derived from Eurocode 2, the glass fibres seems to have some influence of the testing of beams in flexure.

6. Conclusions

Material properties of shotcrete and their development by time have been investigated. Besides result from bond testing and shrinkage testing, data from compressive and flexural strength tests for hardening shotcrete is presented which is not commonly found and can be used in analysis and design work of tunnel linings. It should, however, be remembered that the presented curves fitted to the test data are highly dependent on the actual time scale presented and that extrapolations towards properties for older shotcrete must be avoided. Compressive strength has been investigated for both cast concrete and shotcrete. Flexural crack strength and elastic modulus for shotcrete have been derived from flexural beam tests. New methods for testing bond strength and restrained shrinkage have been developed. A method for studying early age interaction of the interfacial transition zone (ITZ) between shotcrete and a hard rock wall has also been evaluated.

6.1 Basic material properties

Standardized methods were adapted and used for testing of basic material properties, for shotcrete and when appropriate also for cast concrete to make comparisons possible. Slump tests showed that all the tested fibre reinforced shotcrete samples would have been sprayable using the wet mix method. Also, there were no practical problems in spraying the glass fibre reinforced shotcrete slabs for the shrinkage tests. The results showed that cast concrete samples here reached higher compressive strength than corresponding shotcrete samples. There was also a tendency that the glass fibres reduced the compressive strength. The strength of shotcrete in pure tension was not tested due to practical problems in arranging shotcreted test samples for high accuracy results. This material property is however generally of interest for the evaluation of stresses due to restrained shrinkage. Here, this evaluation was done based on re-calculated compressive strength values, based on the relations given in Eurocode 2 (2004). The flexural tensile strength is perhaps a more important property for shotcrete sprayed on hard rock and on soft drains. The results here obtained from flexural test beams showed a tendency to a reduction in strength with increasing degree of glass fibres but also a larger scatter than for the corresponding compressive strength results. No direct tests to establish the elastic modulus was performed but the flexural test results were used to calculate this property in accordance with the tests standard. In this case the results did show significantly lower values than for those recalculated from compressive strengths using the relations given in the Eurocode 2 (2004). The latter values did, however, show good agreement when used in the evaluation of the shrinkage tests. The reason for the deviating results is most certainly low accuracy in the displacement records from the flexural tests. This is in turn caused by a very brittle behaviour of the test beams that were either un-reinforced or contained glass fibres. It should be noted that the evaluation method described in the test standard is foremost intended for use with steel fibre reinforced samples that show a more ductile behaviour. The tests of bond strength and restrained shrinkage were done using the two new methods summarized in the following sections, also containing conclusions with respect to these material properties.

6.2 Bond strength testing

The presented newly developed method was tested, evaluated and proved useful for bond strength testing already from a couple of hours after shotcreting in laboratory environment. The method can also rather easily be adapted to in situ or field environments, to spray shotcrete test samples on granite slabs prepared beforehand. The method is also well suited for producing series of test samples studies of the ITZ between rock and shotcrete strength. The results show that bond strength in general is higher after 72 hours for shotcrete compared with cast concrete, both with and without set accelerator, see Figure 4.9. For cast concrete with accelerator the strength growth is faster up till around 10 hours, thereafter the non-accelerated concrete has a faster development. However, the tendency is a convergence in strength after 72 hours. The shotcrete at +20°C develops faster between 8 hours and 30 hours after which the strength growth for the +20°C shotcrete slows down while that of the +7°C shotcrete continues to increase. However, there is a considerable variation at 72 hours. A comparison of the rate of strength increase of the compressive and bond strength, results shows an initially faster development for the bond strength at +20°C, as can be seen in Figure 5.1. For samples tested at +7°C there is an indication of the opposite during the first 12 hours. However, the number of test results younger than 12 hours are relatively small for this to be a definite conclusion. The distribution of failure modes for the tested samples shows that there was almost no shotcrete remaining on the granite core surfaces in the case of +20°C compared with the test series at +7°C where shotcrete remains on the cores were frequent, indicating lower bond strength relative to tensile strength at low temperatures. This can be caused by the slower hydration process at lower temperature, which was expected. The development of bond strength, or adhesive strength, between shotcrete and rock is complex and depends on the hydration process, which also affects the development of compressive and tensile strength. The micro morphological study of the ITZ between shotcrete and granite shows that the main interaction is physical. The microstructural study of the ITZ shows that there exists no chemical bonding between shotcrete and granite.

6.3 Shrinkage testing

It was shown that the newly developed and tested method realistically captures the behaviour of end-restrained, shrinking shotcrete slabs on soft drains for hard rock in situ. It can also be used to assess the performance of shotcrete fully bonded to a rock surface, with respect to the ability to prevent cracking or to distribute possible shrinkage damage into several fine cracks instead of one wide. Here, it was used in the evaluation of glass fibre addition for avoiding shrinkage cracks and to investigate the sequence of stress build-up that eventually may lead to cracking in shotcreted soft drains. The promising ring test results from Paper IV could not be fully verified in Paper V and the times to crack initiation in the slab tests were also significantly shorter. It should be noted that the most promising results have been observed for concrete rings with a combination of glass and steel fibres. Also, the use of very fine aggregate or filler in the ring tests presented in Paper IV may have contributed to those results. However, the new test method will be useful in the continuous work of finding optimal fibre mixes for reduced shrinkage cracking. It should be noted that the thickness distribution of the sprayed shotcrete layer is a sensitive parameter. Thus, to avoid large scatter in the results there must a high accuracy in the shotcreting procedure. It is important to note that the ring tests performed within the project are not fully comparable with the slab testing methodology, since they describe fully and partly restrained shrinkage, respectively, and this will also have an effect on the time for crack initiation. Free shrinkage has also been tested for both cast concrete and shotcrete, for the latter also with different glass fibre contents. Results are presented in different time scales, 28 and 112 days, and the shrinkage obtained after this time is in accordance with previous observations, see Table 3.2. At all times the shotcrete with highest fibre content showed the largest shrinkage and the un-reinforced reference sample the lowest, see Figure 4.10. One possible reason can be that when glass fibres replace aggregates within a given volume, a reduction of internal restraint towards shrinkage appears.

6.4 Future work

The material properties of shotcrete sprayed on rock need to be further investigated in order to provide more values representative for in situ conditions. Separate creep studies have to be performed, as well as tensile strength studies. More compressive strength tests within 48 hours of shotcrete age should be performed using the stud driving method (Hilti, 2009) at different temperatures. It is also of interest to study the development of shotcrete material properties under different climate conditions, i.e. temperature and humidity conditions which are relevant for tunnel environments. The laboratory test results will provide a reference basis for comparison with future in situ tests, where a great scatter is always found and which is difficult to analyse due to variations in rock quality, rock wall geometry and the shotcreting process.

The new test method for bond strength should also be adapted for use in the field where the effects of set accelerators are of special interest. In further studies the use of appropriate updated pull-out testing equipment with adjustable loading rates should be a priority. An extensive calorimetric study for shotcrete should be performed to receive a more accurate hydration curve for shotcrete. Another interesting method is to perform surface energy measurement according to either the Wilhelmy method or Inverse Gas Chromatograpy (IGC), which have been done earlier on cement paste to investigate the role of chemical and physical forces in the adhesion situation. Such surface energy tests can be complemented by using e.g. x-ray photoelectron spectroscopy (XPS). This energy surface problem is also of interest for the study of different fibre materials and their interaction with cementious materials, to sort out what kind of physical forces that appears in the ITZ. The micro structure of the very young shotcrete, should be studied further, to sort out what physical properties that structure gives, and how that structure influences the real hardening of the shotcrete. Other interesting questions are how the structure is influenced by water desiccation and how this mechanism influences the shrinkage both at early and later times.

The use of glass fibre for shrinkage crack reduction, as presented in Paper IV and V, has to be investigated more in detail. For the future work the main objective will be to find an optimal mix of glass and steel fibres to avoid or reduce shrinkage cracking of shotcreted drainage constructions. Attempts should be made with mixes of both glass and steel fibres and the results compared with tests with fully bonded shotcrete, to see which fibre content is the optimum for different cases, with or without bond, respectively. Shotcreted specimens should be tested in a climate more representative for tunnel conditions, i.e. around +7–8°C and 80 % RH. In situ measurements with instrumentation of strain gauges in a drainage structure should also be performed. The shotcrete layer thickness varied much due to difficulties in the spraying process and the analysis of the thickness variation showed that the minimum thickness of the layer and not the fibre content defines the crack path. How the crack position is correlated with fibre distribution in the cross section area of the shotcrete must be studied further. To secure the input values in laboratory testing a uniform thickness is important. However, the variation in thickness is also an interesting issue because of the irregular geometries in situ. The variation in thickness is certainly the reason why the position of the crack varies since the uneven thickness gives local stress concentrations and this should also be further studied using non-linear finite element modelling.

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I. Bryne, L.E., Ansell, A., Holmgren, J. Laboratory testing of early age bond strength between concrete for shotcrete use and rock. *Nordic Concrete Research, 47, 81-100.*

II. Bryne, L.E., Ansell, A., Holmgren, J. Laboratory testing of early age bond strength of shotcrete on hard rock. *Tunnelling and Underground Space Technology, 41, 113-119.*

III. Bryne, L.E., Lagerblad, B. Interfacial transition zone between young shotcrete and hard rock. *Submitted to ACI Materials Journal, May 2014.*

IV. Bryne, L.E., Ansell, A., Holmgren, J. Investigation of restrained shrinkage cracking in partially fixed shotcrete linings. *Tunnelling and Underground Space Technology, 42, 136-143.*

V. Bryne, L.E., Ansell, A., Holmgren, J. Shrinkage testing of end-restrained shotcrete on granite slabs. *Magazine of Concrete Research, DOI:10.1680/macr.13.00348.*