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STIFTELSEN BERGTEKNISK FORSKNING
ROCK ENGINEERING RESEARCH FOUNDATION

INVESTIGATION AND DEVELOPMENT OF MATERIAL PROPERTIES FOR SHOTCRETE FOR HARD ROCK TUNNELS

Lars Elof Bryne

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Undersökning och utveckling av materialegenskaper hos sprutbetong för bergtunnlar

Lars Elof Bryne, KTH

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Preface

The predominant support method for rock tunnels and rock caverns is shotcrete (sprayed concrete) and bolts. This is a flexible method that can be adjusted to varying site conditions and is utilized both for infrastructural projects as well as for the mining industry. Shotcrete is used in blasted tunnels to stabilize the newly excavated front, a situation when stability is important to maintain for safety and production efficiency. Also, shotcrete is widely used for the continuing permanent support, repair and for maintenance.

The mechanical properties for conventional cast concrete are since long time relatively well known and tested. However, that is not the case for shotcrete even though it is frequently used. In order to better judge the safety at the front short after shotcrete application the time dependent development of bond as well as strength of the material must be possible to assess. Previously, shotcrete properties at realistic conditions were lacking.

This research work was focused on investigating the time dependent material properties for use of shotcrete in hard rock. Primarily, material properties like compressive strength, flexural strength, bond strength and elastic modulus for shotcrete were the goal to determine. Secondly, the goal was to study and measure bond between rock and shotcrete and to investigate and propose a new test method for it. A third goal was to investigate shrinkage, free as well as restrained, for young and hardening shotcrete. The material propertied studied are primarily from own samples that were tested and analyzed.

With the result of this research the branch now has more reliable data for shotcrete properties and its time dependent development. Hereby the strength calculations, both numerical and analytical, are considered more reliable. Also, test procedures have also been developed for bond strength and shrinkage for better control of the actual properties of the shotcrete.

This PhD work was done by Lars Elof Bryne at KTH (Royal Institute of Technology) in 2010-2013 under the supervision of the Professors Anders Ansell and Jonas Holmgren at KTH, division of Concrete Structures. Björn Lagerblad from KTH also participated in the research group. The research was also presented in a Thesis in 2014. A reference group assisted the project and was composed of Kyösti Tuutti (Skanska), Thomas Dalmalm (Trafikverket), Tommy Ellison (Besab) and Per Tengborg (BeFo). The research funding was by the Rock Engineering Research Foundation (BeFo) together with the Swedish Research Council Formas, the Swedish Transport Administration and the Development Fund of the Swedish Construction Industry (SBUF).

Stockholm in October 2014

Per Tengborg

Förord

Den helt dominerande förstärkningsmetoden för bergtunnlar och bergrum är idag med sprutbetong och bult. Det är en flexibel metod som kan anpassas till varierande förhållanden på platsen och används både i infrastrukturprojekt och inom gruvnäringen. Sprutbetong används i sprängda tunnlar för att stabilisera den nysprängda fronten då stabiliteten är viktig att upprätthålla speciellt avseende arbetarskydd och produktionseffektivitet. Men sprutbetong används även i stor omfattning för den efterföljande permanenta förstärkning, reparation och i samband med underhåll.

De mekaniska egenskaperna för konventionell gjuten betong är sedan lång tid förhållandevis väl kända och utprovade, men detsamma gäller inte för sprutbetong trots flitig användning. För att säkrare kunna bedöma om säkerheten vid stuff är fullgod i tidigt skede behöver såväl vidhäftning som hållfastheten kunna bedömas vid olika tidpunkter. Tidigare har det i stort sett saknats uppgifter om sprutbetongens egenskaper under realistiska förhållanden.

Föreliggande arbete har varit fokuserat på att utreda sprutbetongens tidsberoende materialegenskaper vid användning i hårt berg. Det är främst materialegenskaper som tryckhållfasthet, böjhållfasthet, vidhäftningshållfasthet och elasticitetsmodul och dess förändring i tiden som i första hand varit målet med arbetet. I andra hand har målet varit att studera och mäta vidhäftning mellan berg och sprutbetong samt att utvärdera och föreslå en ny provningsmetod för det. Ett tredje mål har varit att undersöka krympning, fri respektive icke-fri, för ung och hårdnande sprutbetong. Materialegenskaper som studerats har till stor del utgått från egna försök som utförts och analyserats.

Resultatet av forskningen är dels att branschen har fått tillgång till tillförlitligare data över sprutbetongens materialegenskaper och dess tidsberoende utveckling. Härigenom blir hållfasthetsberäkningar, såväl numeriska som analytiska beräkningar mer tillförlitliga. Vidare har provningsmetoder utvecklats för vidhäftning och krympning som möjliggör en bättre kontroll av sprutbetongens verkliga egenskaper.

Doktorsarbetet utfördes av Lars Elof Bryne vid KTH 2010-2013 under ledning av professorerna Anders Ansell och Jonas Holmgren vid KTH, betongbyggnad. I forskargruppen ingick också Björn Lagerblad vid KTH. Arbetet presenterades också i en avhandling 2014. Den referensgrupp som bistått utredarna och bidragit med värdefullt stöd har bestått av Kyösti Tuutti (Skanska), Thomas Dalmalm (Trafikverket), Tommy Ellison (Besab) och Per Tengborg (BeFo). Doktorsarbetet finansierades av Stiftelsen Bergteknisk Forskning (BeFo) tillsammans med Formas, Trafikverket och SBUF.

Stockholm i oktober 2014

Per Tengborg

Abstract

In this report 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 microstructure 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

I föreliggande rapport 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 vidhäftnings-hållfastheten 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 dränerings-konstruktioner. 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.

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1. Introduction

Applications for shotcrete (sprayed concrete) can be found in 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. In e.g. Sweden 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 concreted structures require a high degree of workmanship during spraying as well as sophisticated material and other technical design.

1.1 Background

Securing 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 used. Rock surfaces in tunnels and other subspace constructions are often shotcreted 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. 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. In addition, the use of other additives and the underground climate and temperatures also affect the strength growth ratio of shotcrete. 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.

1.2 Previous investigations

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. 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% (Holmgren, 2014), which when accounted for in the design will increase the total cost of the structure. There are relatively few reports on restrained shrinkage of concrete and shotcrete 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 by Bryne et al. (2014bc), and in the compilation by Ansell et al. (2006). Of importance for the shotcrete performance 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 hardening process. Preliminary tests with combinations of steel and glass fibres, see Holmgren and Ansell (2008ab) and Bryne and Ansell (2011), have indicated that it is possible to distribute shrinkage strain resulting in many smaller instead of few wide cracks.

1.3 Current project

The work presented in this report is part of a PhD project carried out at the division of Concrete Structures at KTH Royal Institute of Technology during 2010-13. The results are presented in a PhD thesis (Bryne, 2014) of which this report is an extract. The project is also summarized in five journal papers, by Bryne et al. (2013, 2014abc) and Bryne and Lagerblad (2014). The current report summarizes most of the obtained results, but details on test set-ups, etc. are found in the above-mentioned publications.

The ultimate goal of the work 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 insufficient 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 tests have 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 The shotcrete material

The difference between ordinary cast concrete and sprayed concrete (shotcrete) is the method of placement, which in the latter case is projection using compressed air instead of casting and vibrating. In comparison with cast concrete shotcrete has unique material properties, due to the method of placement but also to the use of set accelerators. The set accelerators will not directly interfere with the major cement reactions (Lagerblad et al., 2010) but instead react with the pore solution of the young cement paste during the dormant period. Alkali-free set accelerators are currently the dominating type at the market. Although the composition of shotcrete is basically the same as in ordinary 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. 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 by Bryne et al. (2013). In young, shotcrete the microstructure and bond strength will change over time as a result of the progress of cement hydration. 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. Drying shrinkage is a long-time 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.

2.2 Wet sprayed shotcrete

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, see Figure 2.1. 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 the tests presented in the following 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 2.2–2.3. For further details on the shotcrete process, see e.g. Höfler and Schlumpf (2004).

Figure 2.1. Tunnel lining of steel fibre reinforced shotcrete. Picture by courtesy of BESAB, Gothenburg, Sweden.

Tunnelinklädnad av stålfiberarmerad sprutbetong. Foto från BESAB, Göteborg.

Figure 2.2. Spraying of a test box with shotcrete.

Sprutning av låda för sprutbetongprovkroppar.

Figure 2.3 Concrete pumping machine, Putzmeister, THOM-KATT (TK 25).
Sprutbetongpump, Putzmeister, THOM-KATT (TK 25).

2.3 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 2.4 that also give examples of synthetic, i.e. plastic, fibres. Steel fibre reinforced concrete was studied by Ding and Kusterle (1999; 2000). Examples on fibre types is given a compilation by 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 by Bryne et al. (2014bc) is shown in Figure 2.5.

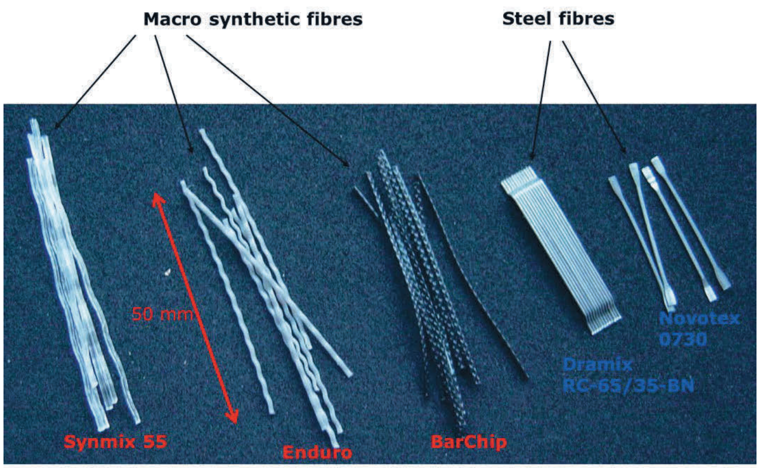


Figure 2.4. Macro fibres – steel fibres and synthetic fibres.
Makrofibrer – stålfibrer och syntettiska fibrer.

Figure 2.5. Micro fibres – here 6 mm long glass fibres.
Mikrofibrer – här 6 mm långa glasfibrer.

2.4 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 2.6. 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 Bryne et al. (2014bc). 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 Figure 2.7-2.8. 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).

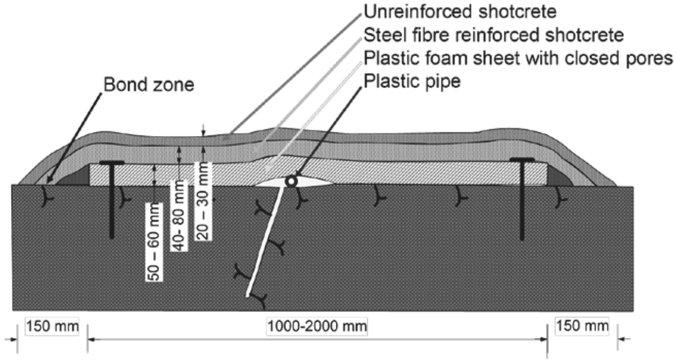


Figure 2.6. Shotcreted drain on rock – one strip of drain mat covering cracks in the rock. From Holmgren and Ansell (2008b).

Betongsprutade dräner på berg – en remsa dräneringsmatta som täcker sprickor i berget. Från Holmgren och Ansell (2008b).

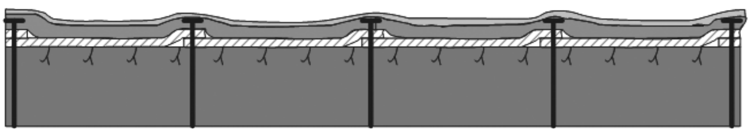


Figure 2.7. Long section of shotcreted drains on rock – drain mats side by side with overlaps. From Ansell (2010).

Lång sektion med dräner på berg – dräneringsmattor sida vid sida med överlapp. Från Ansell (2010).

Figure 2.8. The Southern Link road tunnels, constructed with shotcreted drains. Photo provided by the Swedish Road Administration.

Södra länkens vägtunnlar, konstruerade med betongsprutade dräner. Foto från Vägverket.

3. Material properties from testing

In this chapter all the results for the tests by Bryne et al. (2013, 2014abc) are presented and summarized. The results also connect to the paper by Bryne and Lagerblad (2014) and 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.

3.1 Density and slump

The concrete used in all tests is based on the more or less general recipe shown in Table 3.1. The most important deviation from the basic recipe is made by Bryne et al. (2014bc) where restrained shrinkage has been the issue, with different fibre mixes investigated giving the variance noted in Table 3.1. There is some variation according to aggregate and cement type, and for one of the tests by Bryne et al. (2013) CEM II/A-LL 42.5 R has been used. For all other tests, 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%.

The results in Table 3.2 are taken from Bryne et al. (2014b) 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 3.3 are from Bryne et al. (2014c) and present the slump test results for the sprayed concrete, i.e. shotcrete.

Table 3.1. General recipe and main ingredients for tested concrete.
Grundrecept och huvudsakligt innehåll för provad betong.

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 3.2
Glass fibre	2600	See Tables 3.2-3
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] Bryne et al. (2014bc)

Table 3.2. Slump, density and compression strength of 28 days old 150 mm cast concrete cubes. With various combinations of steel and glass fibres.
Sättmått, densitet och tryckhållfasthet hos 28 dygn gammala 150 mm gjutna betongkuber. Med olika kombinationer av stål och glasfibrer.

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

Sättmått, densitet och tryckhållfasthet för 28 dygn gamla sågade sprutbetongkuber och gjutna referens prov. Med olika innehåll av glasfibrer.

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

3.2 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, 2009). Test specimens sawn from spray boxes for compressive and flexural tests are shown in Figure 3.1. 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 Bryne et al. (2014b). Early age compressive strengths for cast concrete and mortar, presented by Bryne et al. (2013), are compared in Figure 3.2 with the strength for corresponding shotcrete and reference concrete, from Bryne et al. (2014c). Equations for the fitted curves are given by Bryne et al. (2013, 2014ac), respectively. Results for cast concrete and shotcrete with and without glass fibres are presented by Bryne et al. (2014c), 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 3.3. The expressions for the fitted curves, which can be compared to those given by Bryne et al. (2014c), are given in Eqs. (3.1-3.4), for cast samples as:

$$f_{\mathrm{cm,cube}} = 106{,}90\,\mathrm{e}^{-1{,}79/t^{0{,}51}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le \ 112 \text{ days} \qquad (3.1)$$

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

$$f_{\mathrm{cm,cube}} = 76{,}68\,\mathrm{e}^{-1{,}70/t^{0{,}60}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le \ 112 \text{ days} \qquad (3.2)$$

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

$$f_{\text{cm,cube}} = 81{,}41\,\mathrm{e}^{-1{,}86/t^{0{,}53}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le \ 112 \text{ days} \tag{3.3}$$

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

$$f_{\text{cm,cube}} = 65{,}95\,\mathrm{e}^{-1{,}82/t^{0{,}76}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le \ 112 \text{ days} \tag{3.4}$$

Figure 3.1. Test specimens from spray boxes, for compressive and flexural crack strength.
Provkroppar sågade ur sprutlådor, för tryck- och böjdraghållfasthet.

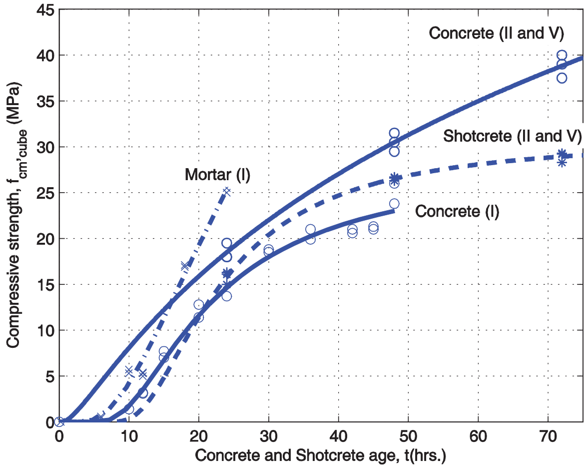


Figure 3.2. Compressive cube strength vs. age for mortar, cast concrete and shotcrete (Bryne et al., 2013, 2014ac).

Kubtryckhållfasthet som function av ålder för cementbruk, gjuten betong och sprutbetong (Bryne m.fl., 2013, 2014ac).

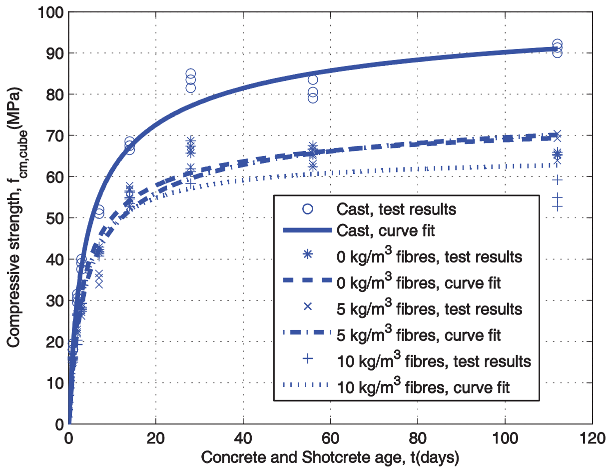


Figure 3.3. Compressive strengths from testing of shotcrete and cast reference samples (Bryne et al., 2014c).

Tryckhållfasthet för sprutbetong och gjutna kontrollprov (Bryne m.fl., 2014c).

3.3 Tensile strength

For the evaluation of shrinkage tests by Bryne et al. (2014bc) 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:

$$f_{ck} = \left(\frac{f_{ctm}}{0,3} \right)^{3/2} \qquad (3.5)$$

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.

3.4 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, 2006). An example of a crack surface generated by a bending test is shown in Figure 3.4. Tiny parts of glass fibre residue are protruding from the failure surfaces of the shotcrete beam.

Results for shotcreted beams with different glass fibre contents are presented by Bryne et al. (2014c), 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 3.5. Also these fitted curves can be compared with those given by Bryne et al. (2014c), 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. (3.6-3.8) gives, for shotcreted samples with 0 kg/m^3 glass fibres as:

$$f_{ctm,fl} = 6,40\, e^{-0,75/t^{0,67}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \qquad (3.6)$$

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

$$f_{ctm,fl} = 7,24\, e^{-0,82/t^{0,44}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \qquad (3.7)$$

For shotcreted samples with 10 kg/m³ glass fibres:

$$f_{\text{ctm,fl}} = 5{,}99\,\mathrm{e}^{-0{,}80/t^{0{,}99}} \quad \text{(MPa)} \quad \text{for} \quad 0 \le t \le \ 112 \text{ days} \qquad (3.8)$$

Figure 3.4. Glass fibre in failure surface of beam tested in bending.
Glasfiberbrott i böjprovad balk.

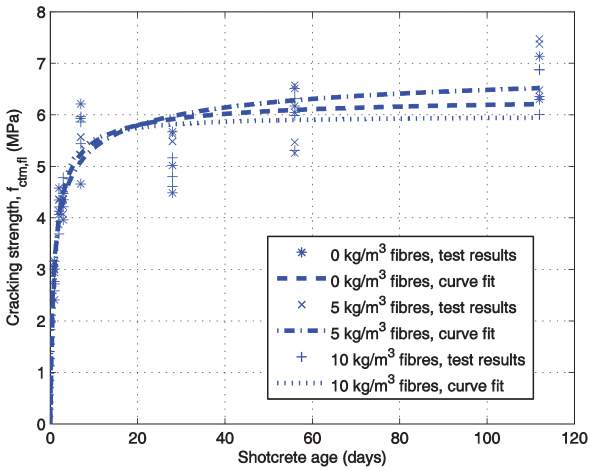


Figure 3.5. Flexural crack strengths from testing of shotcrete (Bryne et al., 2014c).
Böjdraghållfasthet för sprutbetong (Bryne m.fl., 2014c).

3.5 Elastic modulus

Elastic modulus can be estimated on basis of flexural tests according to the *Swedish Standard SS-EN 14488-3:2006* (SSI, 2006). For the test results presented in Figure 3.5 the corresponding elastic modulus results are shown in Figure 3.6. Curves have also been fitted to these data points and for shotcreted samples with 0 kg/m^3 glass fibres the relation becomes:

$$E_{\mathrm{cm}} = 26{,}30\,\mathrm{e}^{-0{,}47/t^{0{,}59}} \quad \text{(GPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{3.9}$$

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

$$E_{\mathrm{cm}} = 28{,}56\,\mathrm{e}^{-0{,}67/t^{0{,}37}} \quad \text{(GPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{3.10}$$

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

$$E_{\mathrm{cm}} = 21{,}32\,\mathrm{e}^{-0{,}53/t^{2{,}01}} \quad \text{(GPa)} \quad \text{for} \quad 0 \le t \le 112 \text{ days} \tag{3.11}$$

The recalculated test results and fitted curves underestimate the elastic modulus when compared to values calculated from the compressive strength tests shown in Figure 3.3, 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 3.5. It should be noted that due to this uncertainty in the registered deformations the evaluation of the test results by Bryne et al. (2014bc) 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:

$$E_{\mathrm{cm}} = 22\left(\frac{f_{\mathrm{cm}}}{10}\right)^{0{,}3} \tag{3.12}$$

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. (3.12) and Figure 3.3 are given in Figure 3.6. The rescaled curves are based on the parameters given in Table 3.4.

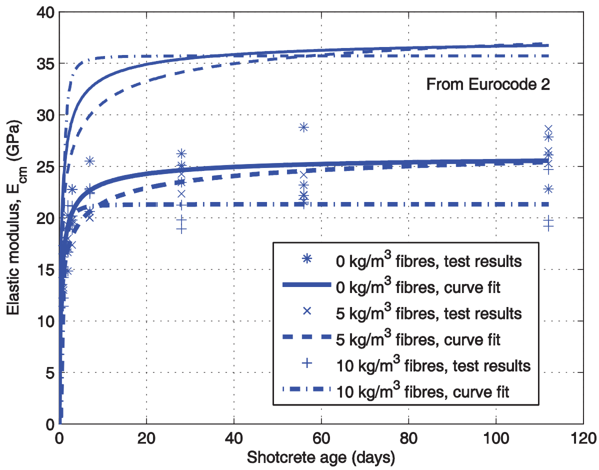


Figure 3.6. Elastic modulus for shotcrete. Calculated from the flexural crack strengths test results (Bryne et al., 2014c). Compared to results calculated from compressive strength (Eurocode 2, 2004).

Elasticitetsmodul för sprutbetong. Beräknad från böjdraghållfasthetsprov (Bryne m.fl., 2014c). Jämförda med resultat beräknade utifrån tryckhållfasthet (Eurocode 2, 2004).

Table 3.4. Elastic modulus for shotcrete estimated from test results for flexural and bending strengths, respectively. With various contents of glass fibres.

Elasticitetsmodul för sprutbetong, uppskattad från böjdraghållfasthetsresultat. Med olika innehåll av glasfibrer.

Test no.	**Steel fibres (kg/m^3)**	**Glass fibres (kg/m^3)**	**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 3.5 & Eqs.(3.9-11)	See Figure 3.3 & Eq.(3.13)	$f_{cm}=0,8(f_{cm,cube})$

3.6 Bond strength

One of the main properties for shotcrete used within the tunnelling sector is the bond strength, which has been studied by Bryne et al. (2013, 2014a) and Bryne and Lagerblad (2014). The main three principles for bond strength testing are shown in Figure 3.7, 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 for Bryne et al. (2013, 2014a) and Bryne and Lagerblad (2014). 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.

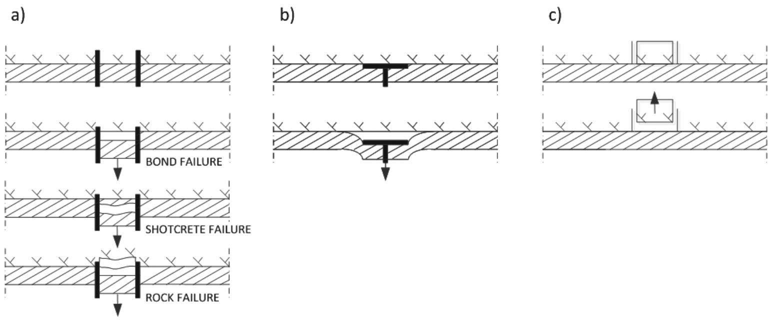


Figure 3.7. Methods for bond strength testing. Pull-out of drilled test cores (a), pull-out of shotcrete covered steel discs (b) and pull-out in the reversed direction of a substrate core (c). From Bryne et al. (2013, 2014a).

Metoder för vidhäftningsprovning. Utdrag av borrade testkärnor (a), utdrag av oversprutad stålplatta (b) och omvänd utdragning av kärna borrad ur underlaget (c). Från Bryne m.fl. (2013, 2014a).

The special boxes used for bond strength testing prior to shotcreting are shown in Figure 3.8, with nine cores in each. The method for use with cast concrete is presented by Bryne et al. (2013) and the details for the developed method for shotcrete by Bryne et al. (2014a). The results obtained by Bryne et al. (2013) for cast concrete, with and without set accelerator, are compared with the results for accelerated shotcrete presented by Bryne et al. (2014a), where tests with two different curing temperatures are included, see Figure 3.9.

Figure 3.8. Special test boxes for bond strength tests.
Särskilt tillverkad låda för vidhäftningsprovning.

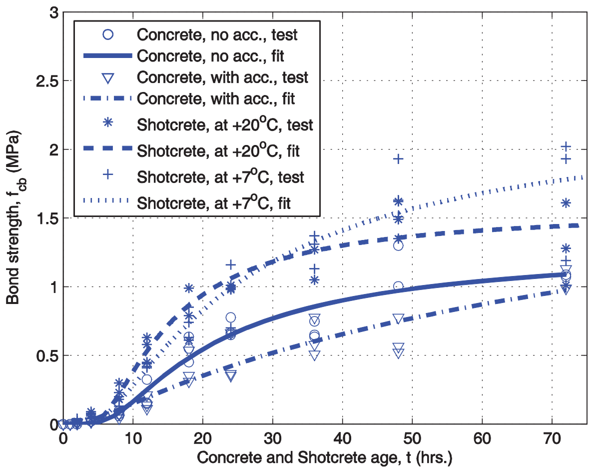


Figure 3.9. Bond strength vs. age for cast concrete with and without set accelerator (Bryne et al., 2013) and for shotcrete at +7°C and +20°C (Bryne et al., 2014a).
Vidhäftningshållfasthet som function av alder, med och utan accelerator (Bryne m.fl., 2013) oich för sprutbetong vid +7°C och +20°C (Bryne m.fl. 2014a).

3.7 Free shrinkage

The free shrinkage has been tested according to *Swedish Standard SS 137215* (SSI, 2000). Details about the production of test specimens are given by Bryne et al. (2014c), 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 by Bryne et al. (2014c), for ages up to 28 days. Also, these test series were continued with measurements at 56 and 112 days of age, resulting in Figure 3.10. The curves fitted are valid from 7 days of concrete and shotcrete age and Eqs. (3.13-16) given below should be compared to the corresponding equations by Bryne et al. (2014c), valid up to 28 days. For cast concrete samples is here:

$$\varepsilon_{sh} = 0,080\, e^{-4,14/(t-7)^{0,42}} \quad \text{for} \quad 7 \le t \le 112 \text{ days} \tag{3.13}$$

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

$$\varepsilon_{sh} = 0,085\, e^{-4,22/(t-7)^{0,42}} \quad \text{for} \quad 7 \le t \le 112 \text{ days} \tag{3.14}$$

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

$$\varepsilon_{sh} = 0,076\, e^{-4,35/(t-7)^{0,50}} \quad \text{for} \quad 7 \le t \le 112 \text{ days} \tag{3.15}$$

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

$$\varepsilon_{sh} = 0,083\, e^{-4,33/(t-7)^{0,50}} \quad \text{for} \quad 7 \le t \le 112 \text{ days} \tag{3.16}$$

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/m^3 samples show the largest and 0 kg/m^3 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 3.10. However, it should be noted the trend is that the cast concrete shows the largest change in shrinkage, also at 365 days.

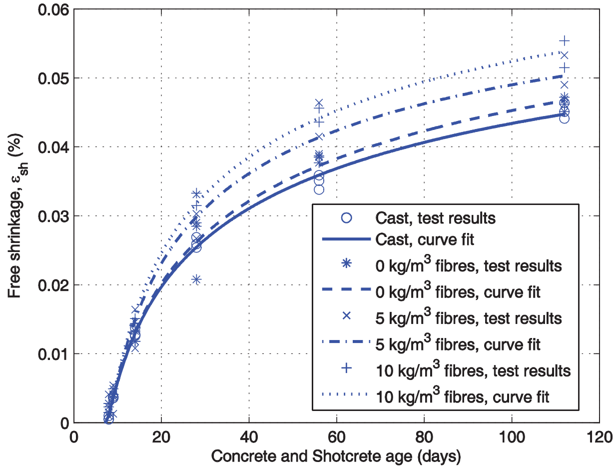


Figure 3.10. Free shrinkage from testing of shotcrete and cast reference samples, from 7 days of age (Bryne et al., 2014c).

Fri krympning, för sprutbetong och gjutna kontrollprov, från 7 dygns alder (Bryne m.fl., 2014c).

3.8 Fully restrained shrinkage

Restrained shrinkage tests with ring specimens as shown in Figure 3.11 are presented by Bryne et al. (2014b). The results shown in Table 3.5 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.

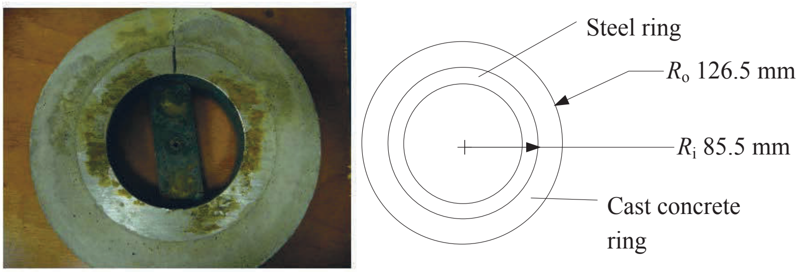


Figure 3.11. A concrete ring with outer radius R_o and an inner radius R_i is simply cast around an internal steel ring with a thickness of 28 mm. From Bryne et al. (2014b).

Betongring med yttre radien R_o och inre radien R_i gjuten kring en inre 28 mm stålring. Från Bryne m.fl. (2014b).

Table 3.5. Results from testing of ϕ253 mm concrete shrinkage rings with various contents of fibre reinforcement. Number of rings with macro cracks and corresponding ages at cracking. Possible occurrence of micro cracks. From Bryne et al. (2014b).

Resultat från provning av 253 mm betongkrympringar med olika fibreinnehåll. Antal ringar med makrosprickor och alder för uppsprickning. Eventuella mikrosprickor. Från Bryne m.fl. (2014b).

Test no.	No. spec.	Steel fibres (kg/m^3)	Glass fibres (kg/m^3)	Macro crack Number of rings cracked	Age at cracking, days	Micro crack 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).

3.9 Partly restrained shrinkage

Restrained shrinkage tests are presented in Bryne et al. (2014bc). In the former, 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 by Bryne et al. (2014c), performed with sprayed concrete, i.e. shotcrete. The principles of the restrained slab test are shown in Figure 3.12. 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 3.13. A shotcreted granite slab, also equipped with the strain gauges connected with monitoring cables, is shown in Figure 3.14.

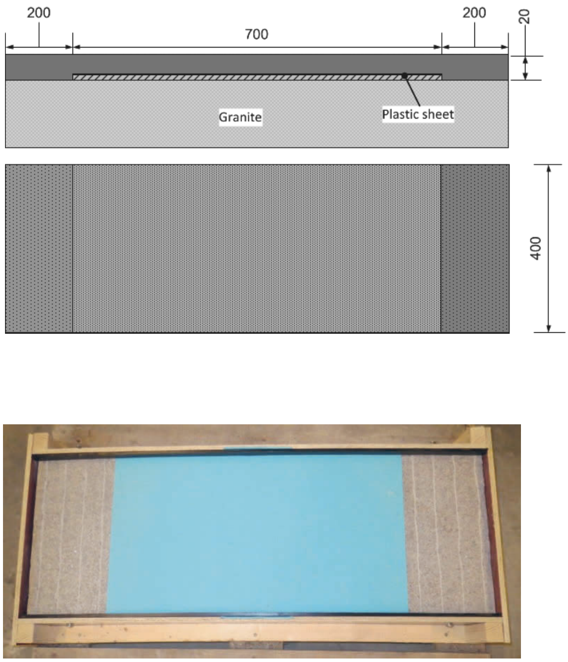


Figure 3.12. End-restrained shrinkage test sample. The de-bonded length is 700 mm.
Ändförankrade krympprovkroppar. Den fria längden är 700 mm.

Figure 3.13. Spraying of test slabs.
Sprutning av provplatta.

Figure 3.14. End-restrained specimen with strain gauges and cables.
Ändförankrad provplatta med töjningsgivare och kablar.

Examples of results from testing of slabs number 1 and 6 are given by Bryne et al. (2014c). 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 3.15. 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 3.16, where also the average shotcrete thickness and crack profiles are shown. The measured strains for all six test slabs are given in Figure 3.17.

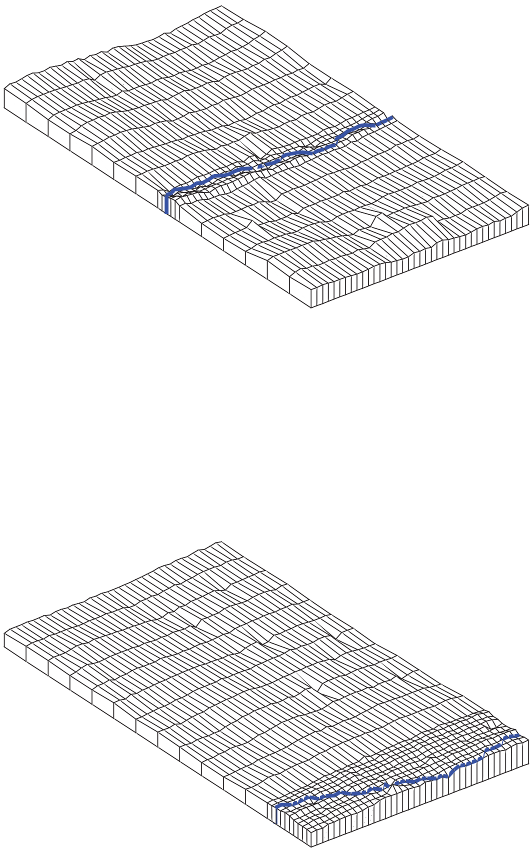


Figure 3.15a. Surface topology for test slabs 1 (top) and 2 (bottom). Cracks are marked with solid, blue lines. The basic horizontal measurement grid is 10×50 mm^2.

Ytstruktur för provplatta 1 (överst) och 2 (underst). Sprickor markerade med blå linjer. Det horisontella mätnätet är 10×50 mm^2.

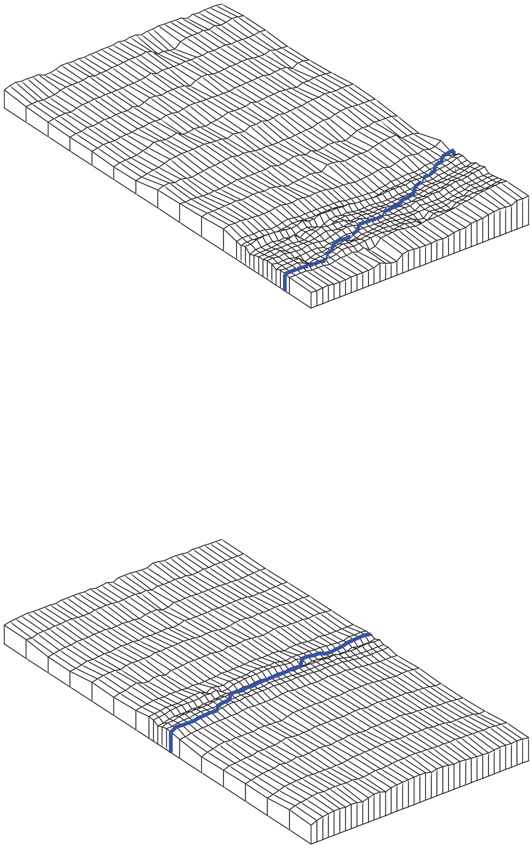


Figure 3.15b. Surface topology for test slabs 3 (top) and 4 (bottom). Cracks are marked with solid, blue lines. The basic horizontal measurement grid is 10×50 mm^2.

Ytstruktur för provplatta 3 (överst) och 4 (underst). Sprickor markerade med blå linjer. Det horisontella mätnätet är 10×50 mm^2.

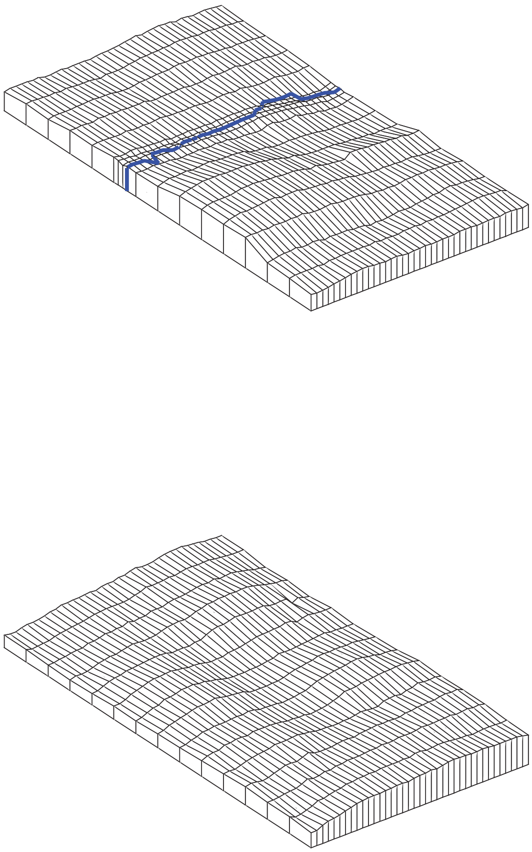
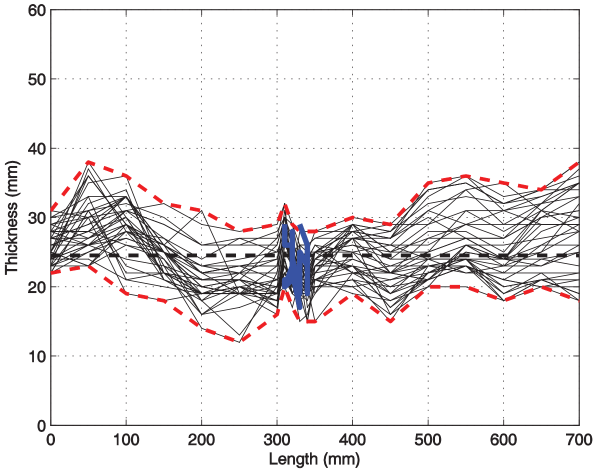


Figure 3.15c. Surface topology for test slabs 5 (top) and 6 (bottom). Cracks are marked with solid, blue lines. The basic horizontal measurement grid is 10×50 mm^2.

Ytstruktur för provplatta 5 (överst) och 6 (underst). Sprickor markerade med blå linjer. Det horisontella mätnätet är 10×50 mm^2.



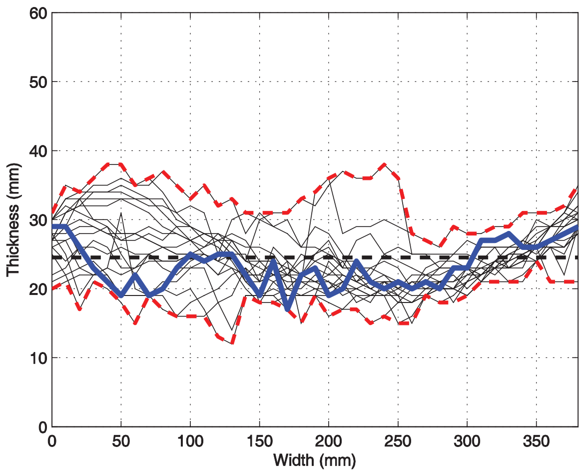
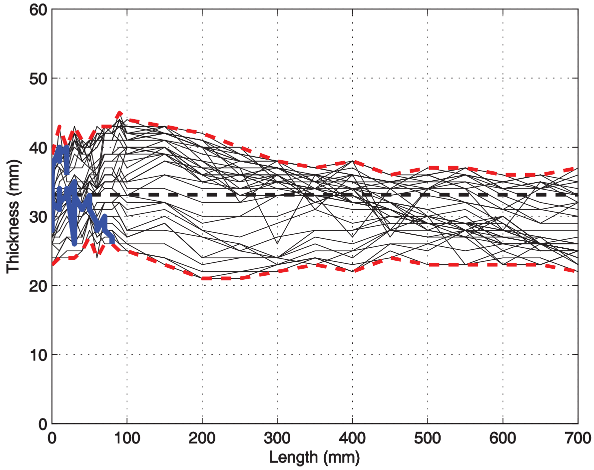


Figure 3.16a. Profiles for test slab 1 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.

Profiler för provplatta 1 – längdsektioner (överst) och tvärsektioner (underst). Sprickor markerade med blå linjer, medeltjockleken med streckad linje.



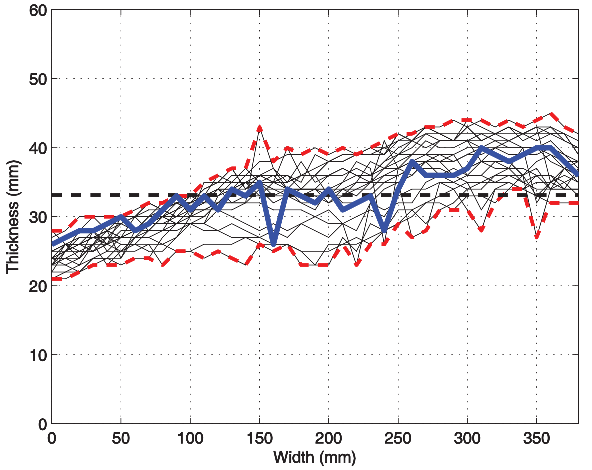
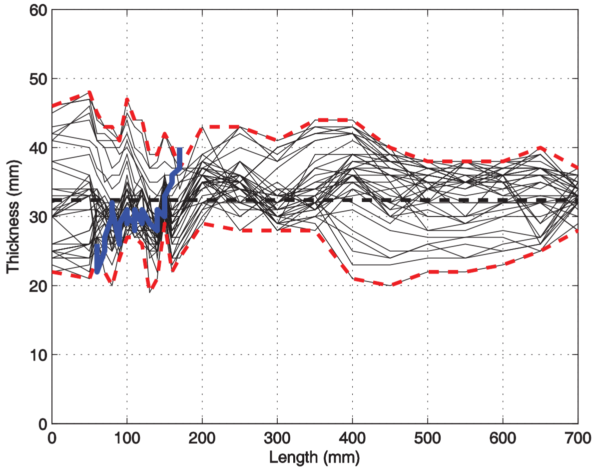


Figure 3.16b. Profiles for test slab 2 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.

Profiler för provplatta 2 – längdsektioner (överst) och tvärsektioner (underst). Sprickor markerade med blå linjer, medeltjockleken med streckad linje.



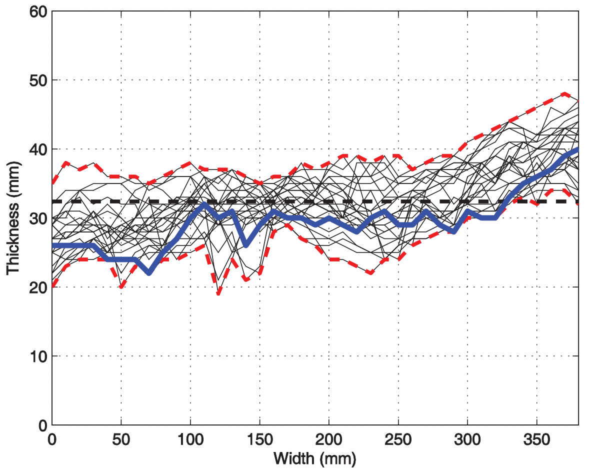
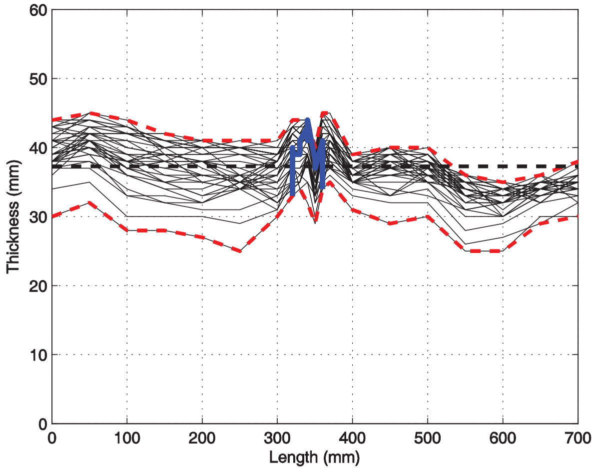


Figure 3.16c. Profiles for test slab 3 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.

Profiler för provplatta 3 – längdsektioner (överst) och tvärsektioner (underst). Sprickor markerade med blå linjer, medeltjockleken med streckad linje.



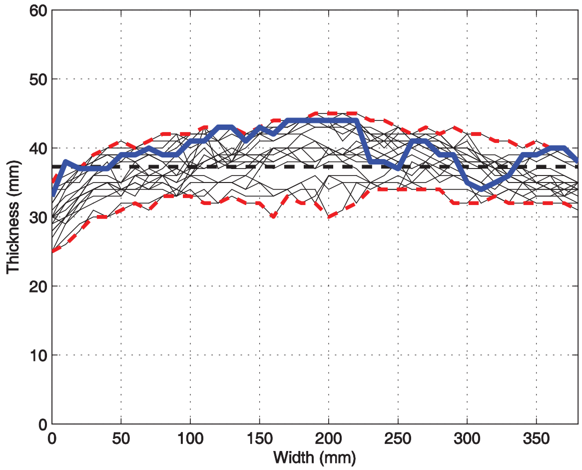
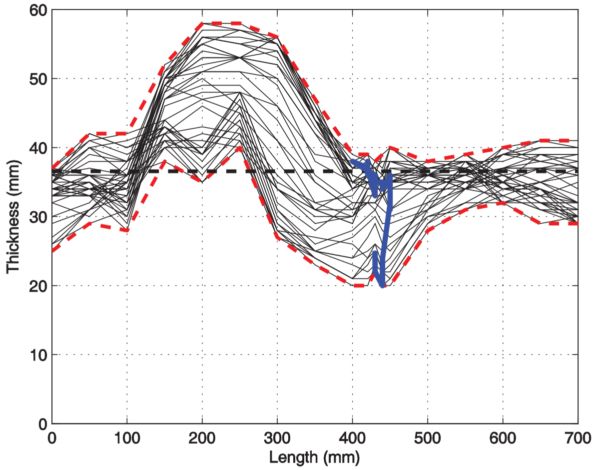


Figure 3.16d. Profiles for test slab 4 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.

Profiler för provplatta 4 – längdsektioner (överst) och tvärsektioner (underst). Sprickor markerade med blå linjer, medeltjockleken med streckad linje.



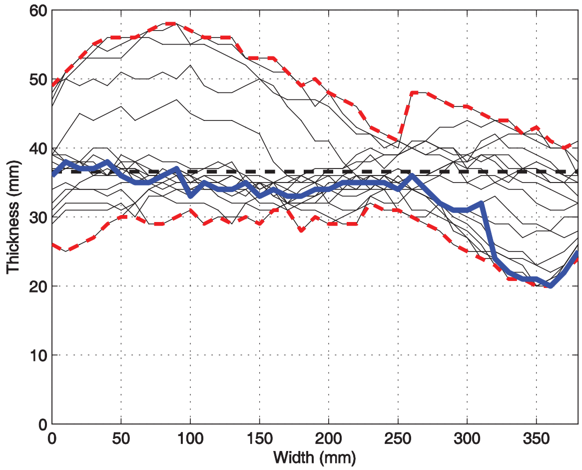
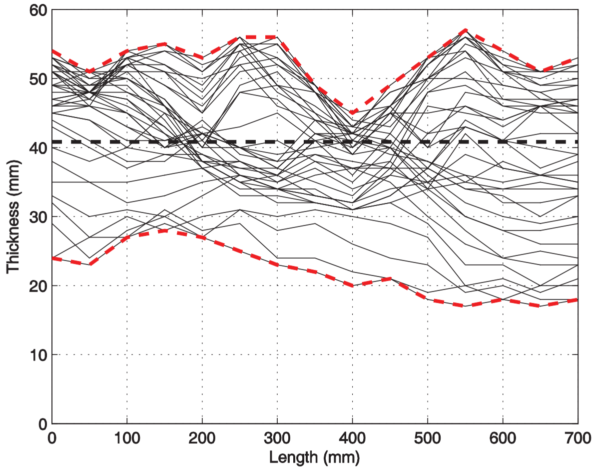


Figure 3.16e. Profiles for test slab 5 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.

Profiler för provplatta 5 – längdsektioner (överst) och tvärsektioner (underst). Sprickor markerade med blå linjer, medeltjockleken med streckad linje.



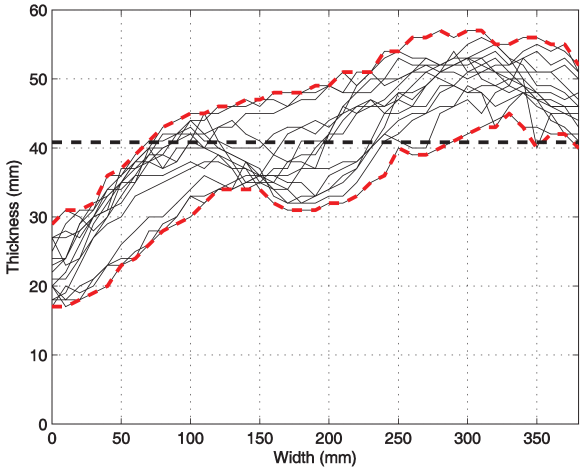


Figure 3.16f. Profiles for test slab 6 – length sections (top) and cross-sections (bottom). Cracks are marked with blue, solid lines, the average thickness with dashed lines.

Profiler för provplatta6 – längdsektioner (överst) och tvärsektioner (underst). Sprickor markerade med blå linjer, medeltjockleken med streckad linje.

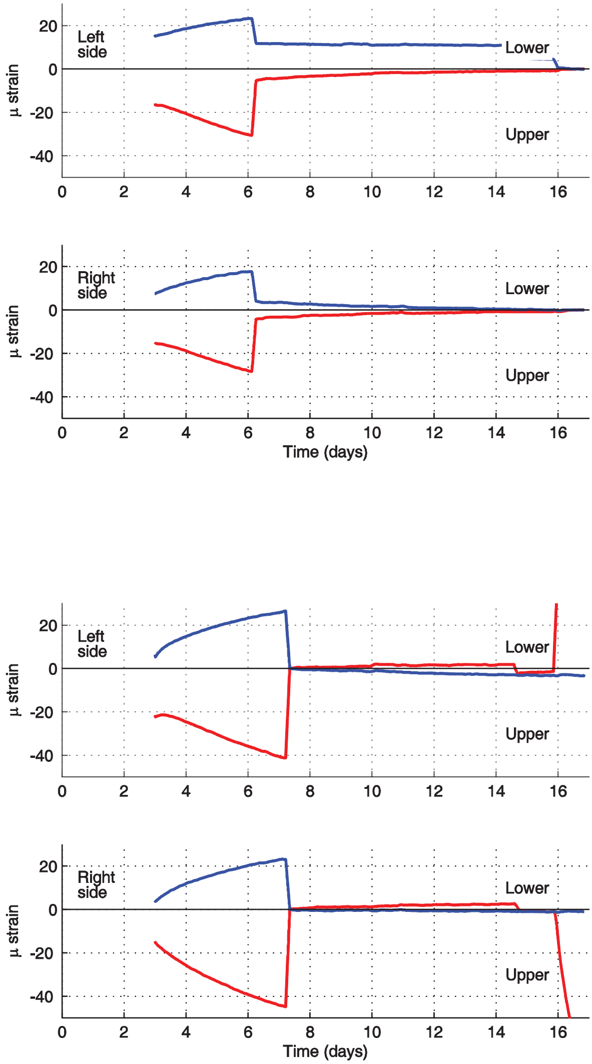


Figure 3.17a. Measured strains for test slab 1 (top) and slab 2 (bottom). From upper and lower strain gauges on left and right side of each slab.

Uppmätta töjningar för provplatta 1 (överst) och 2 (underst). Från övre och nedre töjningsgivare på vänster och höger plattsida.

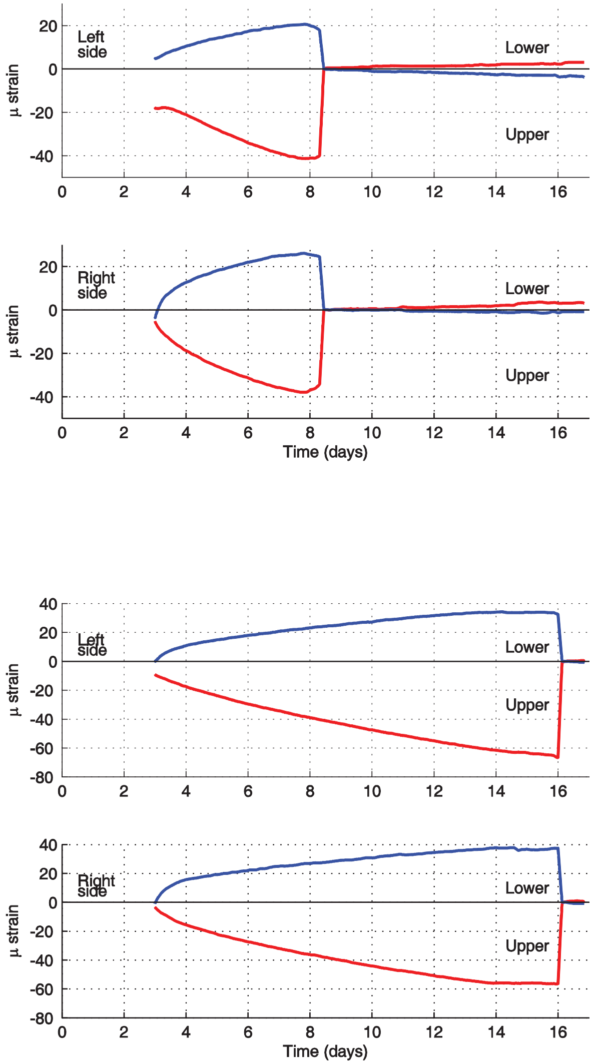


Figure 3.17b. Measured strains for test slab 3 (top) and slab 4 (bottom). From upper and lower strain gauges on left and right side of each slab.

Uppmätta töjningar för provplatta 3 (överst) och 4 (underst). Från övre och nedre töjningsgivare på vänster och höger plattsida.

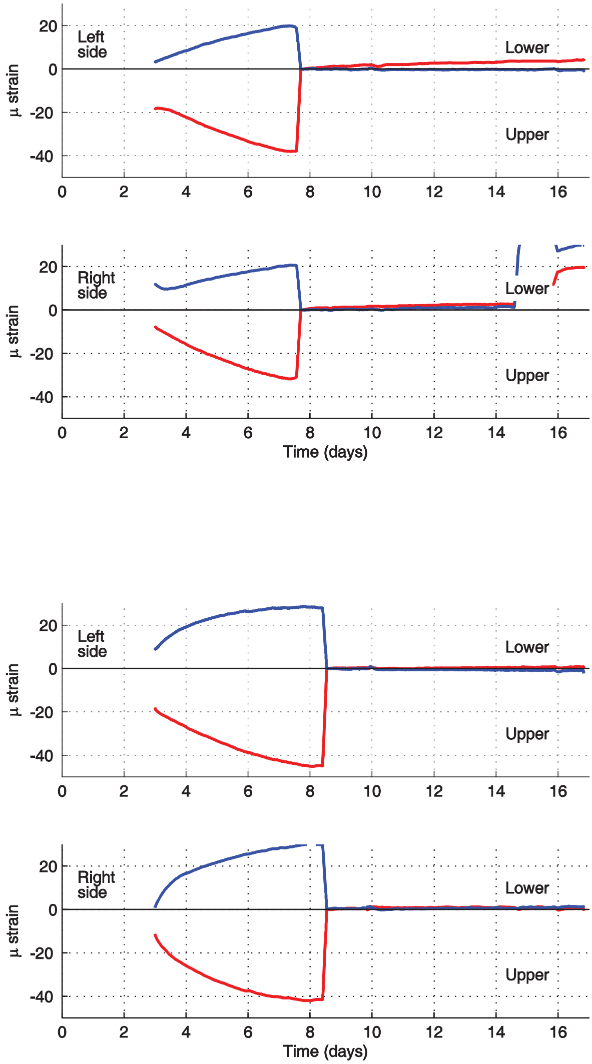


Figure 3.17c. Measured strains for test slab 5 (top) and slab 6 (bottom). From upper and lower strain gauges on left and right side of each slab.

Uppmätta töjningar för provplatta 5 (överst) och 6 (underst). Från övre och nedre töjningsgivare på vänster och höger plattsida.

4. Comments to the results

In the following the results will be discussed and commented, also with a short summary of the contents from Bryne et al. (2013, 2014abc) and Bryne and Lagerblad (2014), with focus on bond strength and restrained shrinkage. Results from bond strength testing are given in section 3.6 (and Bryne et al., 2013, 2014a), but the microstructural investigations presented by Bryne and Lagerblad (2014) is not covered here. The results from shrinkage testing are given in sections 3.7–3.9 (and Bryne et al., 2014bc). The results for density and slump, compressive strength, tensile strength, flexural strength and elastic modulus are commented where appropriate.

4.1 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 3.9 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 3.9, it is obvious that samples with no accelerator develops faster than without accelerator, up to around 8 hours.

In Figure 4.1 the relative compressive and bond strength for cast concrete and shotcrete is given, at temperatures +20°C and +7°C respectively, as presented by Bryne et al. (2014a). 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 3.2–4.3 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.

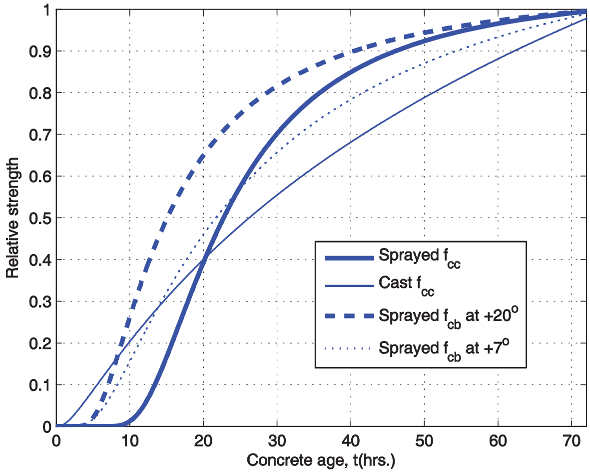


Figure 4.1. Relative strength vs. concrete age of compressive strength for cast and sprayed concrete at +20°C, and bond strength for sprayed concrete at +20°C and +7°C, respectively. From Bryne et al. (2014a).

Relativ hållfasthet som funktion av ålder för tryckhållfasthet för gjuten och sprutad betong vid +20°C och vidhäftningshållfasthet för sprutbetong vid +20°C och +7°C. Från Bryne m.fl. (2014a).

Figure 4.2 is shown by Bryne and Lagerblad (2014) and summarizes the results from the calorimetric study done on a cement mortar with a mix equivalent to the recipe in Table 3.1, but with only sand as aggregate. The speed of hydration has been analysed by isothermal calorimetry (Figure 4.2) 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.

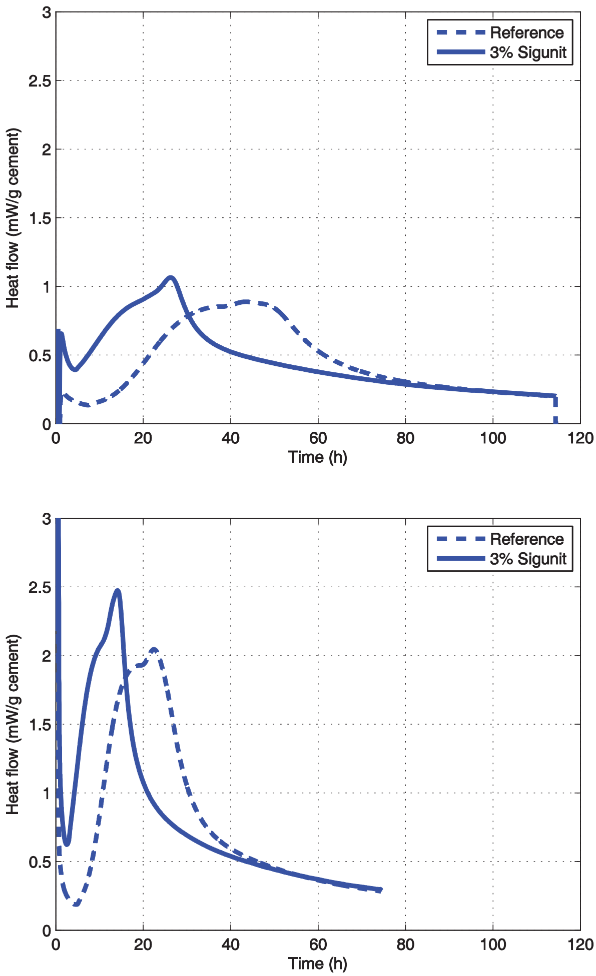


Figure 4.2. Energy release measured by isothermal calorimetry at two temperatures, +8°C (top) and +20°C (bottom), from Bryne and Lagerblad (2014).

Energiutveckling mätt med isotermisk kalorometri vid två temperaturer, +8°C (överst) och +20°C (underst), Från Bryne och Lagerblad (2014).

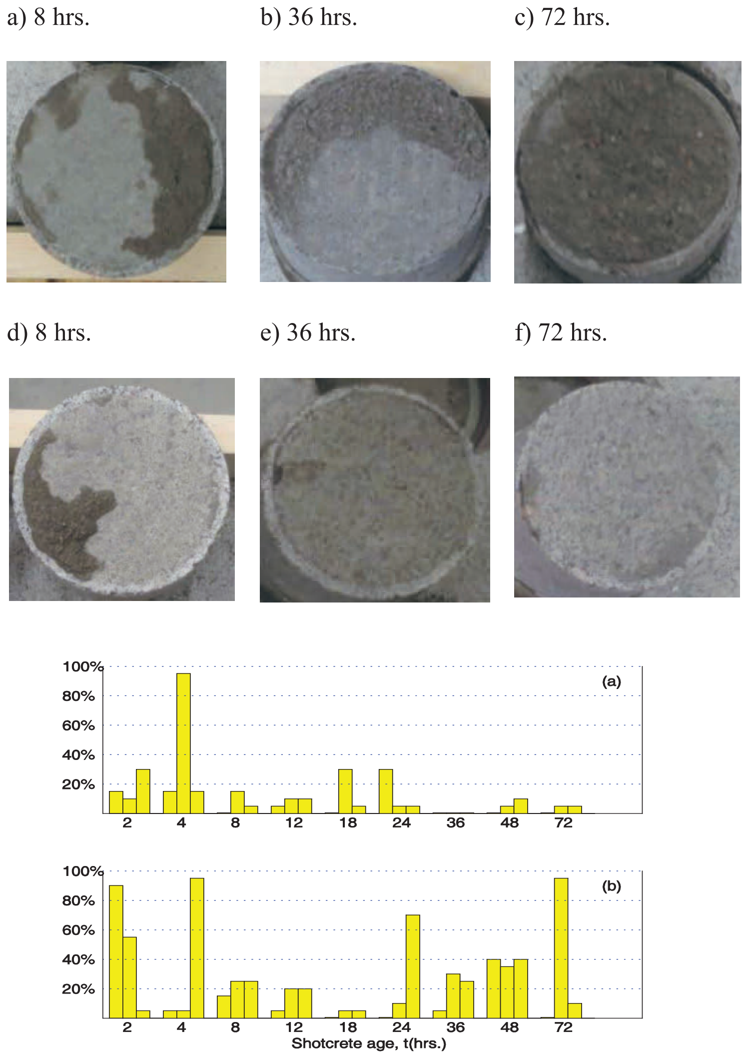


Figure 4.3. Typical failure modes at different temperatures and ages. Specimen (a)-(c) tested at +7°C and (d)-(f) at +20°C. Diagrams showing ratio of remaining shotcrete area on the rock interface after testing, at +20°C (a) and +7°C (b), from Bryne et al. (2014a).

Typiska brottmoder vid olika temperaturer och åldrar. Prov (a)-(c) vid +7°C och (d)-(f) vid +20°C. Diagrammen visar andel kvarvarande sprutbetongarea på bergyta efter provning vid +20°C (a) och +7°C (b), från Bryne m.fl. (2014a).

In Figure 3.9 the bond strength development in the pull-out test (from Bryne et al., 2013, 2014a) 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 (Bryne et al., 2013) and shotcrete at both +20°C and +7°C (Bryne et al., 2014a) has been studied, with almost the same concrete composition as given in Table 3.1. 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 by Bryne et al. (2014a), 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 4.1 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 by Bryne et al. (2014a). 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 4.2 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 4.1. The development of the bond strength for the sprayed concrete in Figure 4.1 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 4.2. However, it should be noted that the calorimetric data in Figure 4.2 represents a minor study.

Some typical failure modes from bond strength testing at different temperatures and ages are shown in Figure 4.3. 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 4.3 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 by Bryne et al. (2014a).

4.2 Shrinkage

According to Figure 3.10, 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 by Bryne et al. (2014b). 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 4.1. Results from strain measurements for all shotcrete mixes.
Resultat från töjningsmätning för alla provade sprutbetongsammansättningar.

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 4.1 the results from the sprayed slab tests are summarized. A comparison of the different profiles in Figures 3.15–4.17 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 by Bryne et al. (2014bc). It is declared by Bryne et al. (2014c) 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.

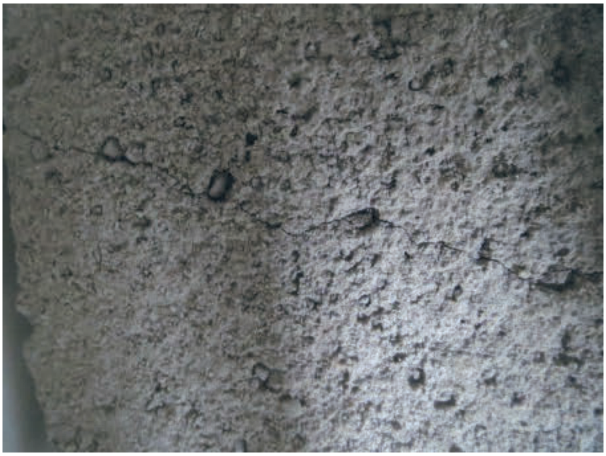


Figure 4.4. Crack formation in slab no 2 showing large aggregate impact pattern.
Sprickor i provplatta nr. 2, med stora synliga ballastkorn.

The photo in Figure 4.4 shows the crack formation at a part of slab 2, see also Figure 3.15 (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 3.5, shows a behaviour of the fitted curves that is quite different compared with the expressions given for a shorter time span in Bryne et al. (2014c). This is also the case for the elastic modulus results shown in Figure 3.6. One interesting detail about Figure 3.6 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.

5. 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.

5.1 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.

5.2 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 3.9. 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 4.1. 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.

5.3 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 Bryne et al. (2014b) could not be fully verified by Bryne et al. (2014c) 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 Bryne et al. (2014b) 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 3.10. One possible reason can be that when glass fibres replace aggregates within a given volume, a reduction of internal restraint towards shrinkage appears.

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BeFo

Box 5501
SE-114 85 Stockholm

info@befoonline.org • www.befoonline.org
Visiting address: Storgatan 19

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