IN SITU OBSERVATIONS AND LABORATORY TESTING OF SHRINKAGE CRACKING IN SHOTCRETE ON SOFT DRAINS

IN SITU UNTERSUCHUNGEN UND LABORTESTS ZU SCHWINDRISSEN IN SPRITZBETON AUF DRAINAGEMATTEN

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In Scandinavian traffic tunnels soft drains covered with shotcrete are often installed to lead away un-wanted water, giving little resistance to shotcrete shrinkage, which may cause severe cracking. Mapping of shrinkage cracks was done in situ, followed by analyses focused on stresses due to drying shrinkage and various time of waiting between turns of spraying, with or without water curing. The effect of dilatation joints has also been investigated. A recently developed laboratory test set-up with shotcrete on instrumented granite slabs represent shrinkage of shotcrete on soft drains. The test results indicate that addition of glass fibres could reduce the cracking problem.

In skandinavischen Verkehrstunneln werden oft Drainagematten mit Spritzbetonüberdeckung zur Ableitung von ungewolltem Wasser verwendet. Der zu geringe Widerstand gegen Schwindrisse führt dabei zu unkontrollierten Rissen im Beton. Hierzu wurden In Situ Aufzeichnungen von Schwindrissen durchgeführt, gefolgt von Berechnungen mit dem Augenmerk auf die Spannungsentwicklung im Spritzbeton während des Schwindens bei unterschiedlichen Wartezeiten zwischen den Spritzlagen, mit und ohne Nachbehandlung. Zusätzlich wurden die Auswirkungen von Fugen untersucht. Eine vor kurzem entwickelte Messeinrichtung, bei der der Spritzbeton auf eine Granitmessplatte aufgebracht wird, repräsentiert dabei das Verhalten auf Drainagematten. Die Testergebnisse zeigen, dass eine Verstärkung des Spritzbetons mittels Glasfasern das Schwindrissproblem reduziert.

1. Introduction

The large and complex transport tunnel systems built through hard rock in Sweden and Scandinavia during the last decades have put focus on maintenance issues. To allow cost efficient operation throughout the life-span of the tunnels the amount of in-leaking water must be minimized. Due to the increased interest in long service life for tunnels combined with a strive to minimize maintenance and repair work there has been an increased use of drain systems that in some cases cover substantial parts of a tunnels surface. These drains and linings are often covered with shotcrete to provide protection against fire and mechanical damage, often designed to withstand bending moment and shear forces through the use of steel fibre reinforcement. This is especially important in railway tunnels where trains pass at high speed causing under- and over-pressure waves that make the drains vibrate [1]. These types of dynamic loads may also arise from heavy traffic in road tunnels. One type of drain constructions that has been used in e.g. Sweden [2–3] consist of a shotcrete covered plastic mat, as described in Figure 1. Soft polyethylen mats with closed pores, 50 mm thick and 1500 mm wide, are used in lengths of up to 5–10 m. These are placed vertically and attached to the rock with steel bolts, often ϕ20 mm rebars. Either single mats are placed over cracks or small areas with water leakage, as shown in Figure 1, or several mats are placed side by side to cover tunnel lengths of up to 10–20 m, as demonstrated in Figure 2. The drains are usually covered with 60 mm shotcrete for protection, often an inner layer containing steel fibres and an outer layer which is unreinforced, [4]. The shotcrete thus bonds to the rock on both sides of the drain mats only and can be regarded as a concrete slab which is free to shrink between two fixed ends.

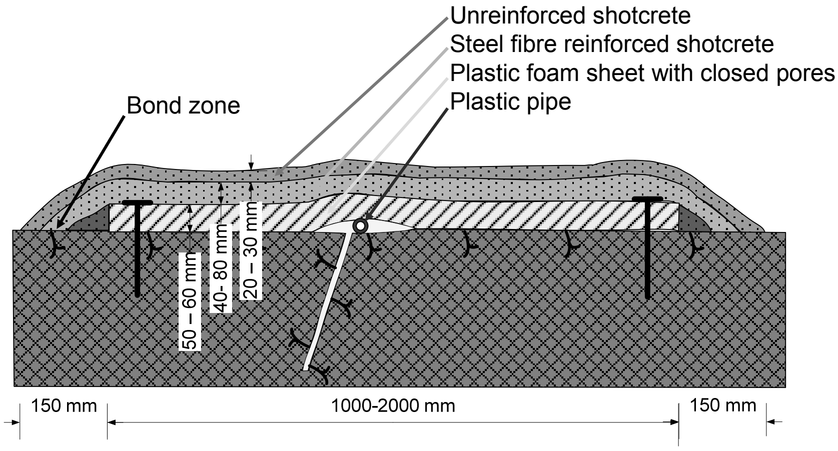

Figure 1: Shotcreted drain on rock – one strip of drain mat covering cracks in the rock. From [5].

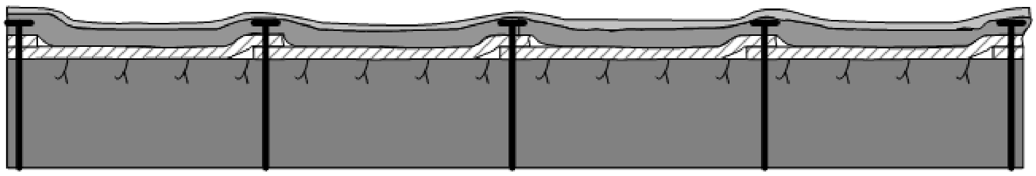

Figure 2: Section of shotcreted drains on rock. Two layers of shotcrete and steel bolts. From [6].

The shrinkage of shotcrete is larger compared to that of ordinary, cast concrete of similar strength due to high cement content and the use of accelerators, making shrinkage cracking in these shotcreted drains a severe problem. Free shrinkage of concrete structural elements does not result in stresses and therefore there is no risk for crack formation. For shotcrete on hard rock the continuous bond at the interface will lead to a distribution of stresses and consequently possible cracks will be relatively thin and distributed over the surface. However, if the subsurface instead consists of a material that makes little or no resistance to the shrinkage strain, such as polyethylene, no crack distribution will occur. This also means that possible cracks will be relatively wide since there is no distribution of strain and the shotcrete on both sides of the crack will become stress free as soon as the crack opens. During shrinkage tensile stresses build up and the magnitude of those depends on the actual shrinkage strain but also on the modulus of elasticity and creep properties of the shotcrete. Young shotcrete has a low modulus of elasticity resulting in low tensile stresses from shrinkage but at the same time the tensile strength is relatively low. Experience show that this can result in cracking, both for unreinforced shotcrete and ordinary steel fibre reinforced shotcrete, i.e. with a fibre content not larger than 60 kg/m^3 [5]. Under normal conditions, such a shotcrete is strain softening and consequently only one, wide crack develops. For long drainage structures of up to 10–20 m length the crack width often exceeds what is acceptable considering durability [7, 8] and cracks with widths of up to several millimetres can develop which may shorten the life time considerably due to corrosion and also decrease the load bearing capacity. To understand the behaviour of these types of drain constructions a number of investigations of shrinking shotcrete on soft drains have been carried out in Sweden. The investigations started with in situ mapping and observations [6] in the Southern Link (Södra länken) tunnels in Stockholm, Sweden, and through analytical studies of the effects of bolt suspension, dilatation joints and uneven shrinkage, [6, 9]. Laboratory tests were made with specimen for restrained shrinkage of shotcrete with steel fibres and also glass fibres, investigating the possibility to distribute shrinkage strain and stresses [5, 7, 10]. As a continuation, a project with experimental investigations of the material properties of young and hardening shotcrete has been carried out, also including the effect of free and partly restrained shrinkage [11–15]. The present paper gives a summary of these results, with examples from published papers and reports.

2. In situ investigation

The investigation of shotcreted drains in the Southern Link tunnels was carried out in 2004, a couple of months before the inauguration of the tunnel system [6, 9]. All sections containing shotcrete covered drains within the six kilometres long tunnel system were documented, giving position, extension and widths of all cracks. For short drain sections, up to 1500 mm, approximately 10 % contained cracks while 50 % of the longer sections each contained 2–5 cracks. Approximately 900 cracks were found of which 60 % had a width larger than 0.5 mm, with an average of 1.2 mm. Also, it was concluded that most shotcrete had normally been watered continuously during 2–3 days after spraying.

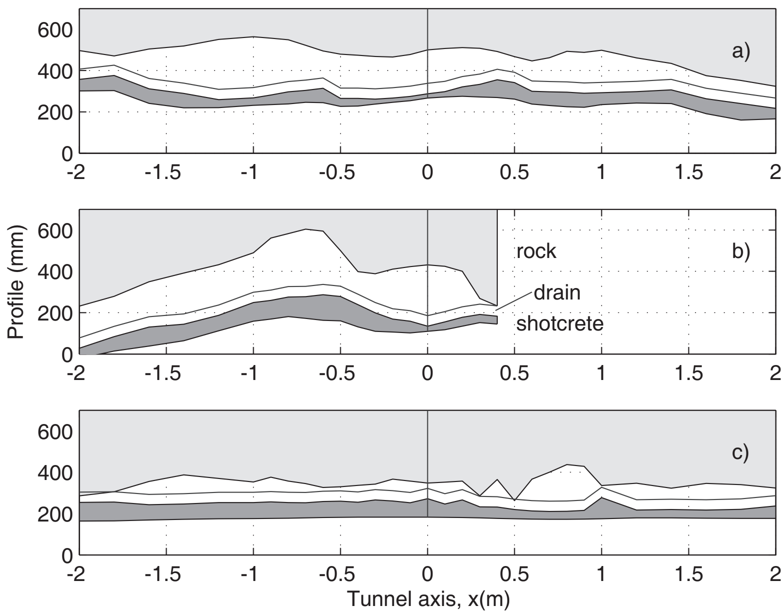

Figure 3: Three examples (a–c) of rock-drain-shotcrete (top to bottom) sections of 4 m length around cracks situated at x = 0. From [6].

Three examples of rock-drain-shotcrete sections are shown in Figure 3. The zero reference level on the vertical axes corresponds to the side of the roadway while the zero position on the horizontal axis marks a shotcrete crack. The inner surfaces of the drain mats are shown with solid lines and note that there are voids between drains and the rock caused by the irregular shape of the latter. The distribution of shotcrete thickness for 480 measurement points is shown in Figure 4, from where it can be concluded that the average thickness was 72 mm, i.e. 12 mm more than intended.

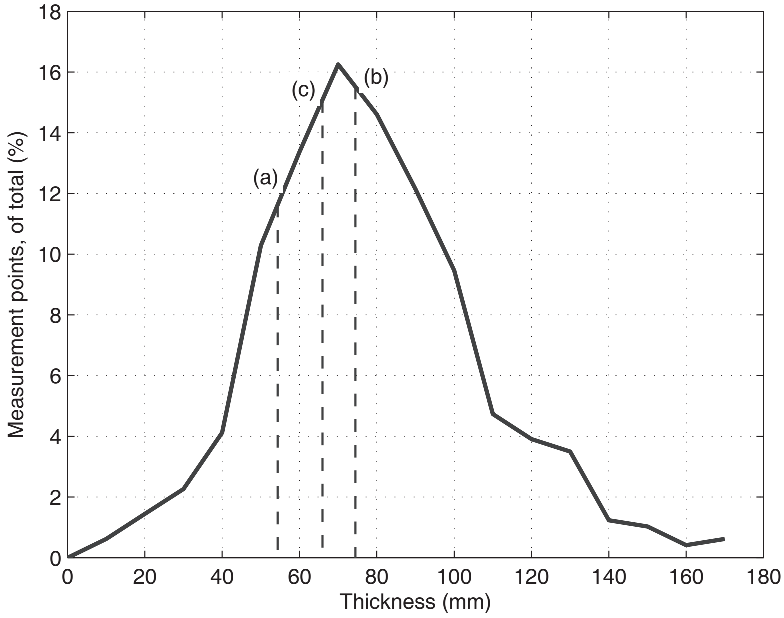

Figure 4: Shotcrete thickness measured in the Southern Link tunnels. The average thicknesses for the three examples (a–c) in Figure 3 are indicated. From [6].

3. The effect of bolt suspension and dilatation joints

The drain mats are kept in place by steel bolts that give a flexible coupling to the rock, due to the elasticity of the mats and the gap between the uneven rock surface and the more harmonic curvature of the mats, see Figure 5. An analytical study of the effect of bolt placement and recommended distance between dilatation joints is presented in [9]. As shown in Figure 5, a section of drain and shotcrete between two cracks shortens due to shrinkage and the bolts will bend which causes restraining forces and stresses in the shotcrete. The relation between bolt length and total length of un-cracked drain-sections can be used to place dilatation joints that can be effective in preventing cracking, as shown by the results in Figure 6. For as short bolt lengths as 50 mm only 1–2 mm of shrinkage displacement is to be expected but for longer bolts this will increase. It can be seen from Figure 6 that a 100 mm long bolt, poorly connected (pinned) to the concrete will lead to around 10 mm displacement, for un-cracked drains almost 50 m long. Thus, long bolts are favourable but the joints must be able to maintain functionality with relatively large shrinkage deformations. The results are calculated for 0.2 ‰ shrinkage, a shotcrete thickness of 60 mm and a distance between ϕ20 mm steel bolts that is 0.75 m.

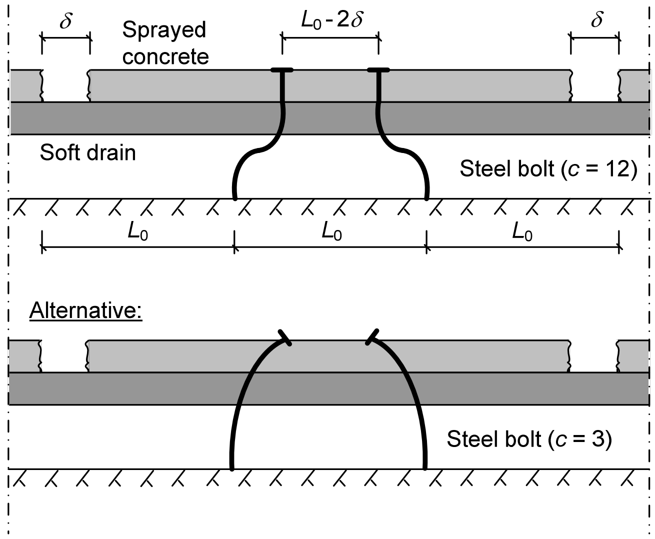

Figure 5: Shrinkage cracking of bolt anchored shotcrete on soft drains. Here c is a stiffness coefficient, depending on the connection between bolt and shotcrete. From [9].

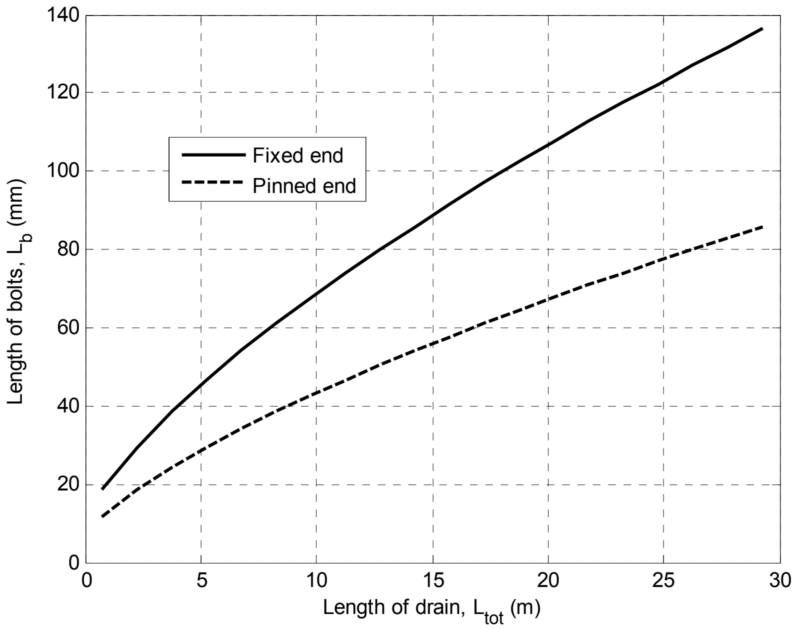

Figure 6: Relation between un-cracked length of shotcreted drain and length of anchoring steel bolts. From [9].

4. The effect of uneven shrinkage

In traffic tunnels one layer of steel fibre reinforced shotcrete is often sprayed with a second, unreinforced layer on top. A study of the shrinkage strains that appear in two layers of shotcrete on soft drains is presented in [6, 9]. The difference in initiation of shrinkage in the two layers will lead to bending stresses in the shotcrete, as described by the models shown in Figure 7. An example of the analytical results is given in Figure 8, representing conditions where watering of the shotcrete is omitted while RH is held constant at 75 %. The first sprayed layer thus begins to shrink immediately after spraying, at the same time as its strength growth is initiated. The tensile stresses (σ_{ct}) appear after both layers have been sprayed. Three combinations of layer thickness are shown, with different waiting times (Δt) between spraying, chosen so that one curve is entirely below the tensile strength (f_{ct}) and one that just exceeds the limit for each case.

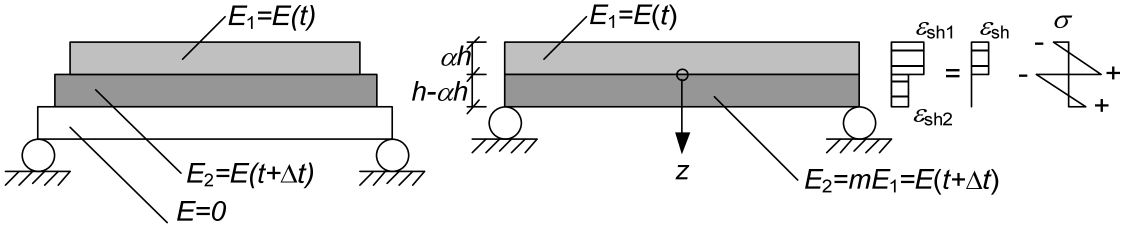

Figure 7: Models of a beam consisting of two shotcrete layers with different shrinkage. A 50 mm thick drain mat is included in the left model. From [6].

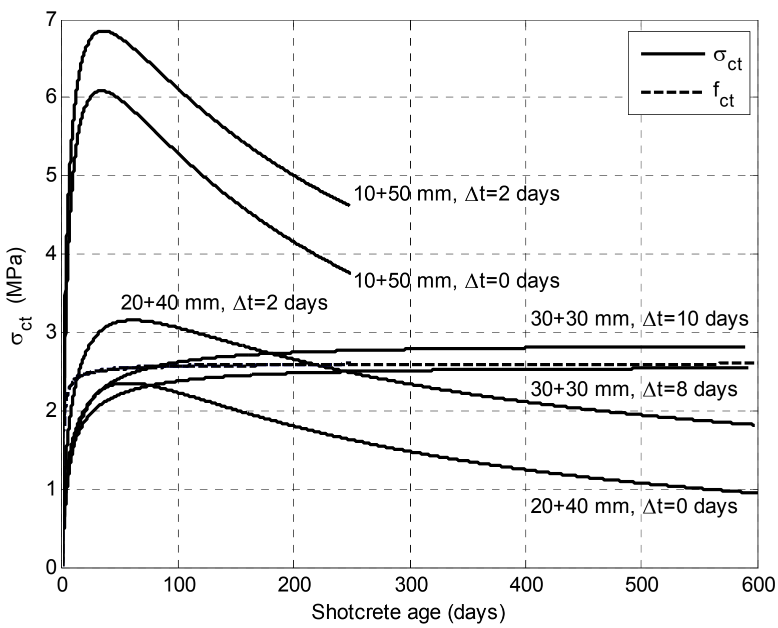

Figure 8: Shrinkage stresses in two-layer shotcrete beams at RH=75 %. The time between spraying and without watering is Δt. The outer layers are 10, 20 or 30 mm and the inner 50, 40 or 30 mm, respectively. From [6].

5. Partly restrained shrinkage tests

Tests that study shrinkage of shotcrete slabs sprayed on soft plastic sheets but with its end sections bonding to a granite slab have been performed in laboratory environment. The method, that has been tested with cast concrete slabs [12] and shotcrete slabs [13], is intended for use in laboratory environment but can also be adopted for in situ conditions, with tests samples sprayed and stored in tunnel environmental conditions. The function is similar to the in situ case with shotcrete over soft drains, using a test set-up as shown in Figure 9. There are not many other methods that are suitable for testing restrained shrinkage of shotcrete and there are no established standard test procedures. The newly developed method is similar to the method described by Carlswärd [16], but here a solid granite slab is used to create the restraining effect at the ends of the test slab. This results in an eccentric compressive normal force which acts on the upper surface of the rock slab, as the result from the shrinking shotcrete layer on top. The slab thus contracts and bends with a linear distribution of strains over its height. The test set-up consists of a 100 mm thick and 1100×400 mm^2 granite slab on which a 700×400 mm^2 and 3 mm thick plastic sheet was placed prior to spraying. Two end areas 200×380 mm^2 provide full bond and anchorage for the shotcrete. Pre-installed strain gauges were placed at the sides of the slab, centrically 10 mm from the upper and lower edges, as shown in Figure 10. The newly sprayed shotcrete was de-moulded after 24 hours and covered with a wet jute cloth and a thin plastic sheet, followed by three days of watering. The sprayed slabs were thereafter kept in a climate chamber with RH of 50 % and +20°C where the shrinkage strains were monitored. The thickness of the shotcrete slabs varied between 20-40 mm, due to the inaccuracy in the spraying process.

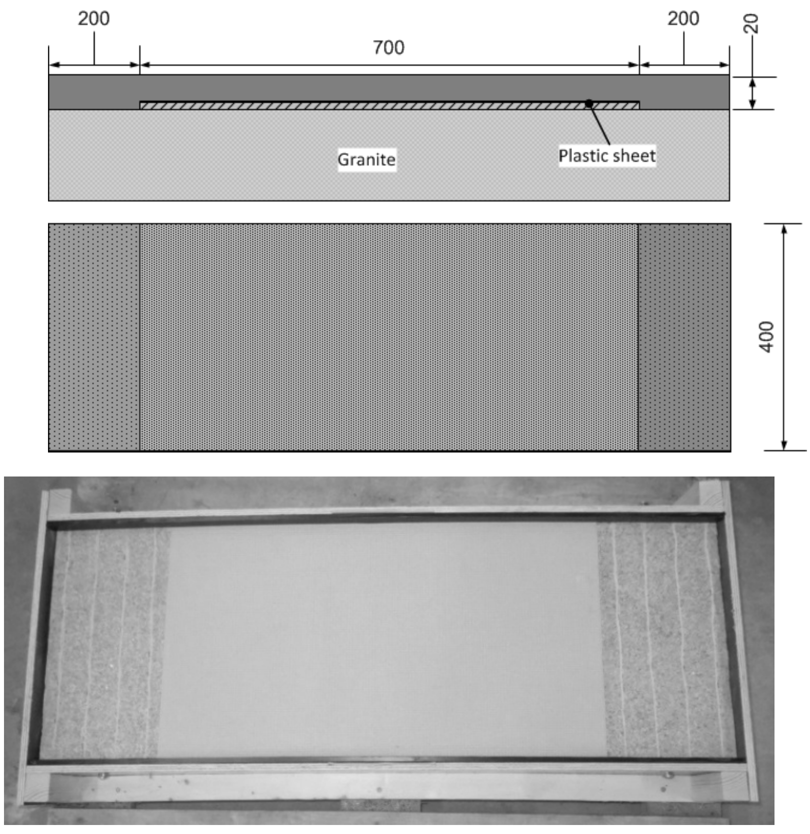

Figure 9: End-restrained shrinkage test specimen with 700 mm de-bonded length. From [13].

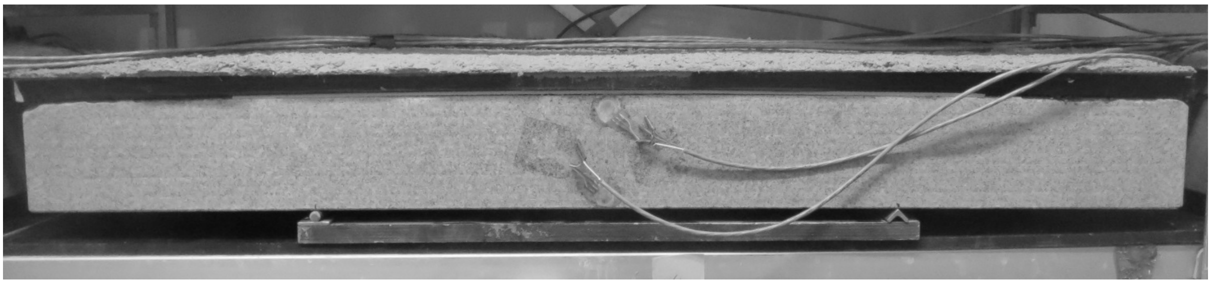

Figure 10: End-restrained test specimen, with shotcrete on granite slab with strain gauges. From [13].

6. Shotcrete properties

Laboratory tests with the set-up described in the previous section have been carried out using wet-sprayed shotcrete [11-13] of similar composition as in Swedish tunnelling, e.g. the Southern link project [6]. As usual in Sweden “Anläggningscement” (cement for civil engineering use) CEM I 42.5 N–SR 3 MH/LA was used for the tests. The test series contained slabs with unreinforced shotcrete and also with glass fibres added in order to see if these could have a crack reducing effect. It is well known that glass fibres devitrify with time at high pH-values, but that has not been considered an important disadvantage, since they are expected to prevent shrinkage cracks during long enough time for the tensile stresses to decrease due to creep. After a year or two most of the shrinkage has taken place and then the contribution provided by the glass fibres is no longer necessary. The general shotcrete mix used is given in Table 1, representing mixes with density of 2255-2285 kg/m^3 and a water to cement ratio of 0.45, also including a set accelerator at 3-5 % of the cement weight. It should be noted that the 6 mm long glass fibres were added in quantities of 5 or 10 kg/m^3, for which relatively good workability was achieved for both these mixes. The amount of aggregates was adjusted due to the inclusion of fibres in the various mixes. See also the results from previous tests by Holmgren and Ansell [5, 7], and Lagerblad et al. [10]. Compressive strength test results for 150 mm cubes are shown in Figure 11 and result from flexural crack strength tests in Figure 12. Prior to testing these samples were kept in a climate of +20°C and a RH of 100% during the first seven days and thereafter at 50% RH. The shotcrete samples were cut out from sprayed boxes.

Table 1: General mix and main ingredients for tested shotcrete.

Material	Density (kg/m^3)	Content (kg/m^3)
Cement	3150	495
Silika Densified	2230	19.8
Water	1000	220
Superplasticiser	1100	3.5
Glass fibres	2600	0-10
Aggregate, 0-2 mm	2650	394
Aggregate, 0-8 mm	2650	1183

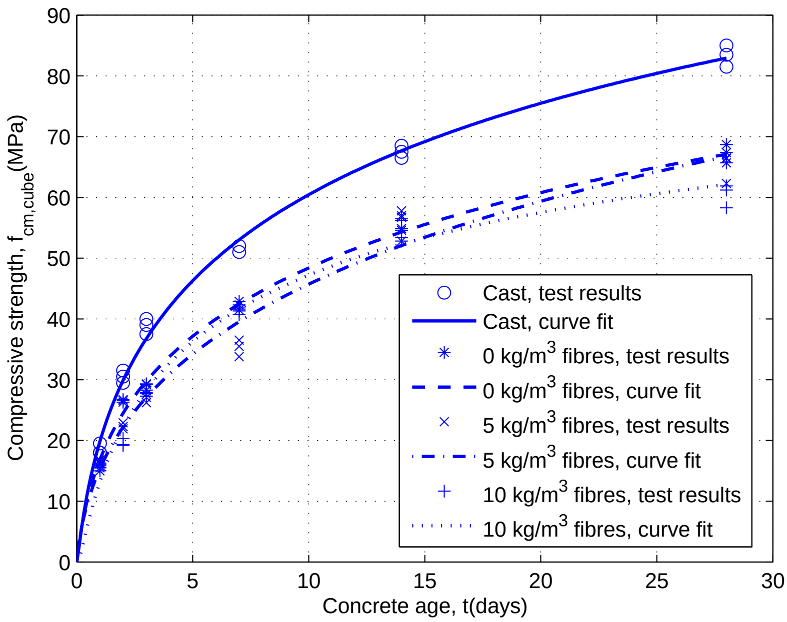

Figure 11: Compressive cube strengths for sprayed and cast reference samples. From [13].

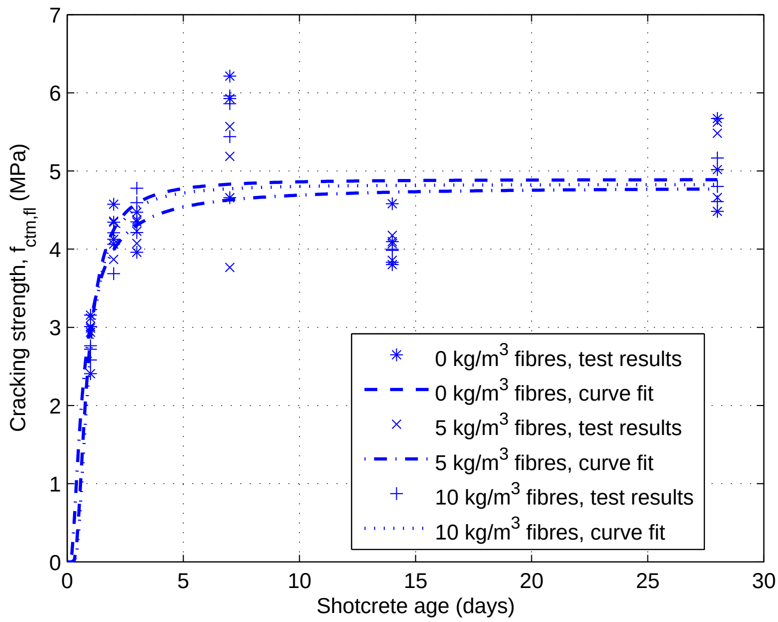

Figure 12: Flexural crack strengths from testing of shotcrete. From [13].

7. Shrinkage test results

The test series with unreinforced and glass fibre reinforced shotcreted test samples [13, 14] consisted of six slabs. Here two slabs have been chosen as representative examples. Slab no. 1 is unreinforced while no. 4 contains 5 kg/m^3 glass fibres and their surface topology and profiles are given in Figures 13-14. As can be seen the average thicknesses of the slabs were 25 mm and 37 mm, respectively. These two slabs showed shrinkage cracks across their centre sections, with no secondary cracks or any sign of bond loss at the ends. The strains in the granite slabs at the upper and lower measurement points (ε_U and ε_L) respectively, are given in Figure 15 where it can be seen that cracking in slab no. 1 occurred after six days while no. 4 stayed un-cracked for 16 days.

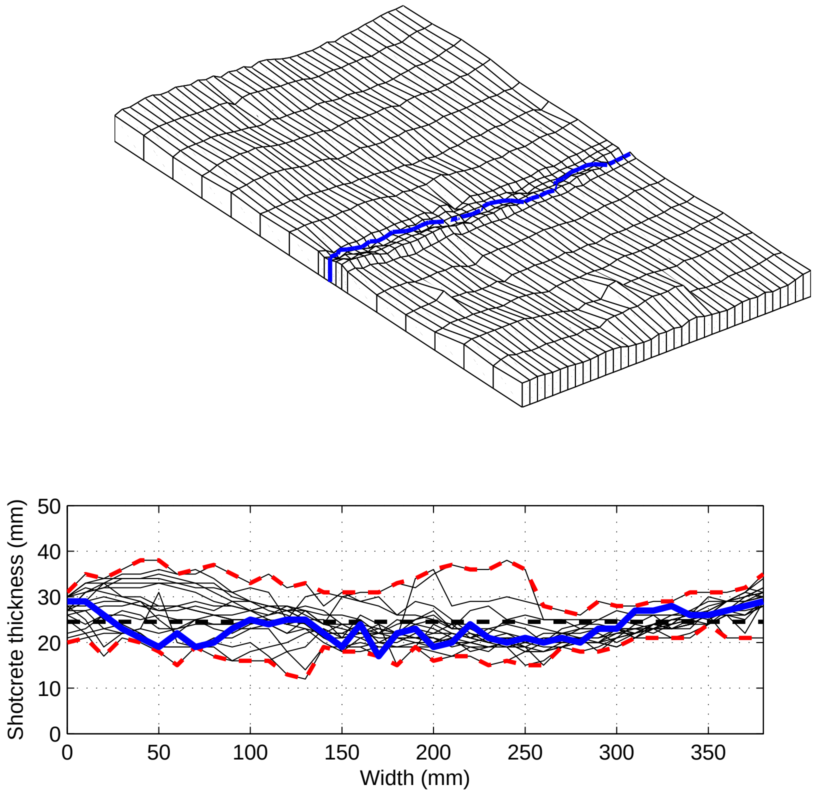

Figure 13: Surface profile and shotcrete thickness for unreinforced *test slab (no. 1). Crack drawn with solid line, mean thickness with a straight dashed line. From [13].*

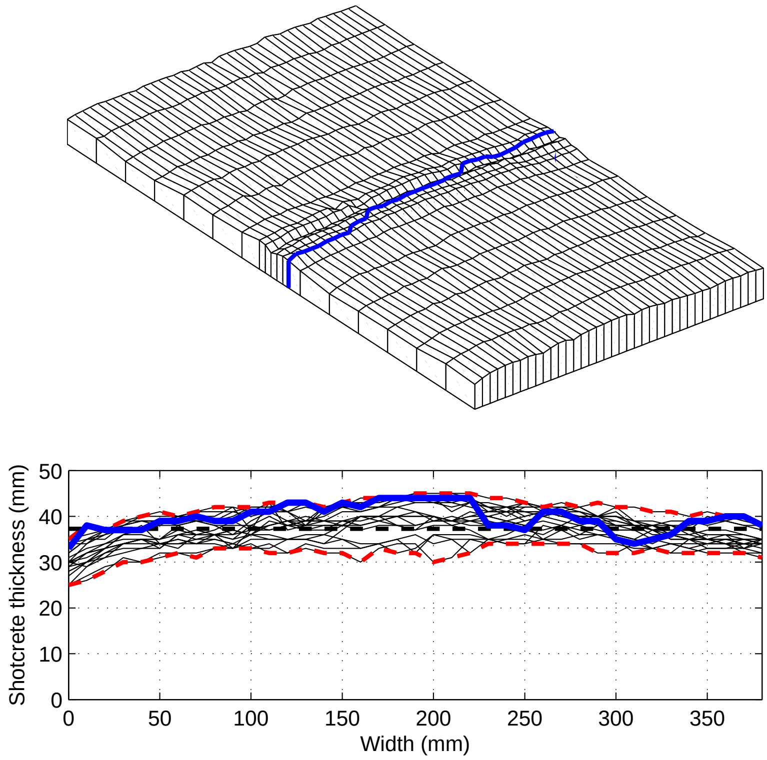

Figure 14: Surface profile and shotcrete thickness for glass fibre reinforced test slab (no. 4). Crack drawn with solid line, mean thickness with a straight dashed line. From [13].

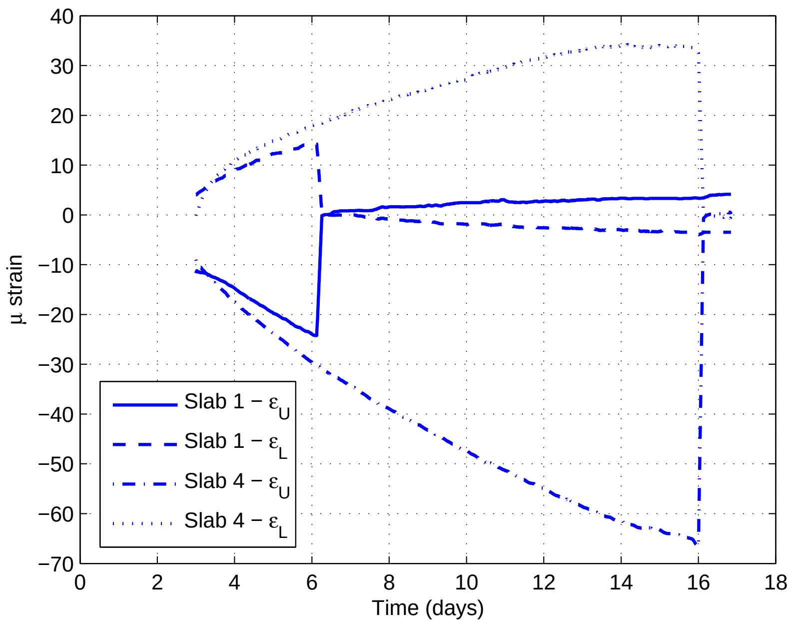

Figure 15: Measured strains for test slabs 1 (unreinforced) and 4 (reinforced), at upper (U) and lower (L) strain gauge positions. From [13].

8. Summary and conclusions

It has been observed that the use of shotcreted drains can lead to severe cracking problems if the design of the drains and the construction process are unfavourable. The result can be a large number of cracks and crack widths that exceed what can be accepted with respect to expected technical service life, and in some cases also from a safety perspective. The major problem with this type of drain construction is that almost all the shrinkage deformation will be concentrated to a weak section where the first crack appears since there is no other restraint than at the ends of the drains. This differs from a case with shotcrete on rock, with many thinner cracks due to the bond between shotcrete and rock.

In situ measurements and observations [6, 9, 15] showed a large number of shrinkage cracks. It was concluded that these were the result of partly restrained shrinkage and thickness variations in the shotcrete. It was seen that the first crack in most cases was situated at a weak section and also that the average thickness of the shotcrete on drains exceeded what was prescribed but at the same time varied significantly. After appearance of a first crack the soft polythene drain mats cannot distribute the shrinkage strain over the length resulting in few wide cracks instead of many thinner ones. This becomes especially troublesome for long sections of drains that will show wide cracks. The most important conclusion with respect to design and construction is that it is important to keep the shotcrete thickness uniform over long sections of drains and also to avoid sharp edges where the drain mats overlap.

To avoid wide shrinkage cracks mechanical dilatation joints can be installed which leads to low stresses in the shotcrete between the joints. However, the joints must be water-tight, allow for approximately 10 mm of deformation and get placed correctly. Studies [9, 15] show that the need of spacing between joints depend on the thickness of the shotcrete, its tensile strength, the amount of shrinkage, dimension and length of the anchoring rock bolts. Under normal conditions and with bolts elastically fixed to the shotcrete it can be recommended that the joints should be spaced closer than 8 m. For rigidly fixed bolts a distance of less than 6 m is recommended. The placement of dilation joints thus depend on the connections between shotcrete and drain mat via the washer (plate) of the bolts used for anchorage in the rock. The washers are usually designed to grip into the shotcrete to provide a mechanical bond. It should be noted that long bolts, i.e. large distances between drain mat and rock surface, are favourable, see e.g. Figure 3.

It is well known that watering will delay the shotcrete shrinkage but has no effect on the strength development. Watering between subsequent turns of spraying is important in order to avoid cracking, which have been studied for combinations of thick and thin layers of shotcrete [6, 9, 15]. Important factors are here the water content of the young shotcrete, the relative air humidity, the air temperature and shotcrete thickness. A thin, outer layer on top of a significantly thicker will always show some degree of cracking. The lowest stresses appear in constructions with two layers of shotcrete of identical thickness. For such a case watering can be omitted for several days without risk of shrinkage crack initiation. From this study it was concluded that maximum shotcrete stresses are to be expected around 30-60 days after watering. However, cracks can appear as early as a couple of days after spraying if the conditions are not favourable.

The newly developed test method for shrinking shotcrete has been evaluated through laboratory tests [11-15] and proved valuable for investigating shrinkage properties of different material mixes. The measured strains and corresponding stresses show good correspondence with material strength properties for the tested shotcrete and the test results demonstrate how the build-up of strains and stresses develops until the first shrinkage crack appears. Here, the first cracks occurred already after 1–2 weeks which is in accordance with in situ observations [6]. The strain measurement shows a linear strain increase which corresponds to build-up of elastic restraining stresses in the shotcrete up to cracking at which full unloading occurs. The registered strains are also comparable with those measured in situ. The maximum strains of 110–180 µstrain (0,110–0,180 mm/m) from the laboratory tests should be compared with 100–300 µstrain (0,100–0,300 mm/m) from the mapping of cracks in the Southern link.

The presented method will be useful for investigation of how to obtain optimal fibre mixes in order to minimize cracking in e.g. young shotcreted drain constructions. The results from inclusion of glass fibres this far indicate a difference between specimen with and without fibres but do not fully verify earlier results with cast specimens [5, 7] which show that 10 kg/m^3 could be enough to prevent cracking. Thus, the main objective of the following work will be to find an optimal mix of glass fibres, possibly in combination with steel fibres. The size of the granite slabs used in the test set-up makes it possible to store the specimen in climate rooms, or in underground tunnelling in situ conditions to evaluate the shrinkage behaviour under various climate conditions. Thus far, conditions with room temperature and controlled humidity have been used but for further testing climates representative for tunnelling conditions, i.e. around 7-8°C and 80 % RH, must be considered.

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