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Investigation of restrained shrinkage cracking in partially fixed shotcrete linings

Lars Elof Bryne *, Anders Ansell [1], Jonas Holmgren [2]

KTH Royal Institute of Technology, Div. Concrete Structures, SE-100 44 Stockholm, Sweden

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ABSTRACT

This study investigates shrinkage of accelerated shotcrete (sprayed concrete), especially in the case of shotcrete sprayed on drains, a part of a tunnel lining not continuously bonded to the rock. One of the goals is to find methods of avoiding shotcrete shrinkage cracks in such drain structures. If cracks yet develop the crack distribution is of great importance, i.e. several fine cracks instead of one wide. By using both steel and glass fibres this may be achieved. A newly developed test set-up for shrinking, end-restrained shotcrete slabs is also presented and evaluated. The performed tests show that the addition of very fine glass fibres could be a solution to the cracking problem. The newly developed test equipment using concrete interacting with an instrumented granite slab represents a realistic way of testing restrained shrinkage. The on-going research focuses on the optimization of the glass fibre addition and the understanding of the interaction between shrinkage and creep of shotcrete.

1. Introduction

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

1.1. Background

As with all types of concretes and cement based materials shotcrete will shrink during its hardening. The reasons are autogeneous shrinkage and drying shrinkage which are results of chemical reactions, development of the cement paste, and evaporation of water, see e.g. Lagerblad et al. (2010). Free shrinkage of concrete structures will not be a problem, but most real structures have restraints imposed on their possibilities for volume change, for example shotcrete that bonds to a rock surface. Restrained shrinkage will lead to stress build-up which may result in concrete cracking, to which also thermal volume changes in hardening concrete may contribute. Experiences from tunnelling projects have shown that extensive shotcrete cracking can occur which substantially reduces the performance and life span of the rock support system, if not immediate repairs are made. Thus, there is a need for a better control of the shrinkage properties of shotcrete, especially since the shrinkage of shotcrete is larger compared to ordinary, cast concrete due to large cement content and the use of set accelerators. It is desired that the shotcrete material is strain hardening in the cracked state, 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 often exceeds what is acceptable considering durability, see e.g. Ansell (2010, 2011).

* Corresponding author. Tel.: +46 8 790 8043.
E-mail addresses: lars-elof.bryne@byv.kth.se (L.E. Bryne), anders.ansell@byv.kth.se (A. Ansell), jonas.holmgren@byv.kth.se (J. Holmgren).
[1] Tel.: +46 8 790 8041.
[2] Tel.: +46 8 790 7948.

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Shotcrete often covers the entire rock surface in a hard rock tunnel but this lining cannot be used to fully prevent water leakage and therefore the rock has to be sealed using grouting prior to blasting. In most cases there will still be water leaking into the tunnels and systems of drains are often installed to lead away un-wanted water that can have a deteriorating effect on the rock support and other installations, and also be a disturbance to and safety risk for traffic in the tunnels. The focus on long technical life-spans leads to an increased interest for using long sections of drains or water shielding linings that cover substantial parts of tunnel walls and ceilings (Holmgren, 2010). These drain systems are often covered with shotcrete to provide protection against fire and mechanical damage and must also be designed to withstand bending moments and shear forces. In order to avoid fatigue the design is made using elastic analysis, but steel fibre reinforcement is used for extra safety. This is especially important in heavily trafficked road tunnels and railway tunnels where heavy vehicles or high speed trains cause air pressure waves that make the drains vibrate (Holmgren, 2004). In most cases the drains are not continuously bonded to the rock and the shotcrete shrinkage is only restrained by fixation areas several meters apart. A drain structure composed by plastic sheets or strips covered by shotcrete can thus be regarded as a slab, which is free to shrink between two fixed ends. The fixation leads to formation of tensile stresses in the shotcrete due to the restrained shrinkage and the risk for cracking depends on the growth rate of the tensile strength and elastic modulus but also on the creep properties of the shotcrete. Young shotcrete has a low modulus of elasticity which causes low tensile stresses from shrinkage but at the same time the tensile strength is relatively low. For drain structures with a length of several meters 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 in the tunnel (Holmgren and Ansell, 2008a).

1.2. Previous investigations

Due to uncertainties and lack of knowledge with respect to the material properties of hardening and shrinking shotcrete on rock an extensive project investigating the material properties of shotcrete has been started in Sweden, Holmgren and Ansell (2008a and b), Lagerblad et al. (2010), Bryne and Ansell (2011), Bryne et al. (2013). The project aims at a better understanding of the mechanisms behind shrinkage and the goal is to reduce the problem while maintaining the sprayability and other important properties of shotcrete. Laboratory tests were made on specimens for restrained shrinkage of shotcrete with steel fibres and also glass fibres, investigating the importance of fibre reinforcement and the material composition regarding the shrinkage and cracking behaviour of hardening shotcrete, Holmgren and Ansell (2008a,b), Bryne and Ansell (2011). The laboratory tests were performed using cast concrete with rheology similar to that of wet mix shotcrete, i.e. sprayable concrete. The tests are performed as traditional ring tests, i.e. concrete are cast in ring-shaped moulds with a stiff steel core preventing free shrinkage of the hardening concrete ring. This paper also presents results from the first tests with a newly developed, larger scale test set-up that more accurately captures the behaviour of shrinking shotcrete, or in this case cast concrete, on plastic drains. The test results will be used as an important reference for forthcoming tests with sprayed shotcrete, for which the method is adapted.

2. Shotcreted drains

Different alternatives for collection of in-leaking 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), Holmgren (2010). This paper focuses on a system of shotcreted drains based on soft polythene mats that are bolted to the rock and then covered with shotcrete, as described in the following sections. It should be pointed out that the present study addresses shrinking shotcrete sprayed on soft substrates that give little restraint on shrinkage displacements but with rigid end connections, a model that describes many of the drainage systems that prevent bond over most of the interface area between rock and shotcrete.

2.1. Single drain systems

The type of drain structure studied here consists of 50 mm thick, 1000–2000 mm wide mats of polythene with closed pores. These soft drain mats come in lengths up to 5–10 m and are placed vertically on rock walls, attached with rock with bolts, as shown in Fig. 1. The bolts are often ϕ20 mm steel rebars spaced 1200 mm, thus providing contact between the mat and the irregular rock surface at single points only. Between drain mat and rock surface there will be small or large voids that may, for example, contain plastic drain pipes or other installations, as shown in Fig. 1. The drains are in most cases covered with shotcrete as protection against mechanical damage and fire, usually an inner layer containing steel fibres and an outer un-reinforced layer. The total shotcrete thickness is often 60 mm, bonding to the rock on both sides of the drain mats only (Holmgren, 2004). The shotcrete is designed to function in the elastic state but the steel fibre reinforcement is required to decrease the risk for fallout of shotcrete sections in the case of overload.

2.2. Long drain systems

The increased interest in maintenance issues for large tunnel systems has lead to an increased use of drains. For cases with water leakage from closely spaced cracks, drain mats of the type previously described are placed side by side to cover substantial parts of a tunnel surface, as shown in Fig. 2. The mats are placed with overlaps to cover tunnel lengths of up to 10–20 m (Ansell, 2010). Such a drain section will provide a dry and ice-free environment for e.g. traffic in the tunnel by diverging in-leaking water to a permanently installed drainage system. The drawback of the design is that the polythene mats form a long, soft and continuous substrate for the covering shotcrete that will start to shrink immediately after spraying. In comparison to shotcrete on rock the low elastic modulus of the polythene will provide almost no restraint on the shrinkage, opposite to the bond between rock and shotcrete. This can lead to the formation of large tensile stresses between the end sections, where the shotcrete is anchored to the rock through bond. Thus, the first shotcrete crack will in most cases appear at a weak section and almost all the shrinkage deformation will be concentrated to that section, resulting in few wide cracks instead of many thinner as on shotcrete fully bonded to rock.

2.3. In situ investigations

In situ investigations of shotcreted drains in the Southern Link (Södra länken), so far the largest highway tunnel project completed in Sweden, were carried out before its inauguration in late 2004 (Ansell, 2010). The drain types used were short and long drains, as described in the previous two sections, but see also Karlsson and Ellison (2001) for further technical details. In situ measurements and observations showed that the shotcrete thickness varied significantly and that the average was 72 mm, i.e. 12 mm more than intended, with a standard deviation of 27 mm. It was also evident that the reason for the large number of cracks found was restrained shrinkage. Approximately 900 shotcrete cracks were found of which about 60% had a width larger than 0.5 mm,