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Investigation of shrinkage cracking in shotcrete on tunnel drains

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ABSTRACT

The presented investigation combines in situ observations, measurements, testing and theoretical modelling. The in situ work was done to map and evaluate the shrinkage related cracking of shotcrete on short and long sections of soft, plastic drains. The occurrence of variation in shotcrete thickness and crack widths were of particular interest. The theoretical analysis focuses on the stresses that can occur due to uneven drying shrinkage in the two-layered shotcrete. The models used include variation in shotcrete thickness and in time of waiting between turns of spraying, with or without watering of the shotcrete. Watering will delay the shrinkage but has no effect on the strength development. Long times of waiting without watering before spraying a second layer will increase the tensile stresses in the shotcrete. It is recommended that the further work is directed towards establishing guidelines for the design of future drain constructions with shotcrete. Different methods for repair and strengthening of cracked shotcreted drains must be developed, tested and evaluated.

1. Introduction

Shotcrete (sprayed concrete) is used in tunnels to stabilize and secure the rock but cannot be used to fully prevent water leakage and therefore the rock has to be sealed using injection prior to blasting. These measures are, however, in most cases not enough to minimize the amount of water that leaks into a tunnel and systems of drains are often installed to lead away un-wanted water from the shotcrete. The large and complex transport tunnel systems built in Sweden and elsewhere during the last decade have put the focus on maintenance issues. The geometry and functions of tunnels are often optimized to allow cost efficient operation throughout the life-span which has lead to an increased interest for using long sections of drains or waterproofing linings covering substantial parts of the walls and ceilings of the tunnels (NVF, 2008). The choice between single drains, longer sections of drains or linings must be done with the tunnel construction process in mind. Instalment of single drains will cause interruptions in the construction work whereas a systematic use of multiple drains, or other lining systems, will give an efficient, repetitive and more controlled process, but with a higher cost for materials. Drains and other linings are often covered with shotcrete to provide protection against fire and mechanical damage. Shotcrete covered drains are also 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 (Holmgren, 2004). These types of dynamic loads may also arise from heavy traffic in road tunnels.

As soon as shotcrete is sprayed, it starts to harden and consequently also to shrink. Due to large cement content the shrinkage of shotcrete is larger compared to ordinary, cast concrete. This is worsened through the use of set accelerators making shrinkage cracking in shotcreted drains a severe problem. A drain structure composed by strips covered by shotcrete can 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. The magnitude of those stresses 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 which causes low tensile stresses from shrinkage but at the same time is the tensile strength relatively low. Experience show that this results 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 (Holmgren and Ansell, 2008a). Under normal conditions such a shotcrete is strain softening and consequently only one, wide crack develops. For long drainage structures the crack width often exceeds what is acceptable considering durability (Holmgren and Ansell, 2008b). Drain structures which have a length of up to 10–20 m can develop cracks with widths up to several millimetres and this can shorten the life time considerably due to corrosion and also decrease the load bearing capacity because of a more unfavourable moment distribution, e.g. when affected to the air pressure fluctuations from passing vehicles in the tunnel (Holmgren and Ansell, 2008a).

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Nomenclature

C	cement content in concrete
E	modulus of elasticity
E_i	modulus of elasticity for material in layer i
f_{cc}	compressive strength
f_{cc}^{28}	compressive strength at 28 days
f_{ct}	tensile strength
h	shotcrete thickness, height of beam
h_m	theoretical thickness
k_s	geometric parameter
m	stiffness ratio
RH	relative humidity
t	time, concrete age
t_s	time for initiation of drying
t_{50}	time until 50% of final shrinkage
Δt	waiting time between spraying turns
T	air temperature
W	water content in concrete
z	vertical coordinate
α	thickness ratio
ε_{cs}	drying shrinkage strain
ε_{s0}	free shrinkage (reference shrinkage)
ε_{sh}	net shrinkage strain
ε_{shi}	shrinkage strain for material in layer i
ε_0	strain at mid-height in beam
κ	curvature at mid-height in beam
γ_{RH}	humidity parameter
γ_s	shrinkage parameter
γ_t	time parameter
γ_T	temperature parameter
σ	normal stress
σ_{max}	maximum normal stress

Motivated by this background a number of investigations of shrinking shotcrete have been started in Sweden, aiming at better understanding of the mechanisms behind shrinkage. 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 accelerated shotcrete (Holmgren and Ansell, 2008a,b). The present paper summarizes an investigation that combines in situ observations and theoretical modelling of restrained shrinkage in two layers of shotcrete on soft plastic drains. The goal is to gain an understanding of the shrinkage process and to establish recommendations for planning of the sequence of spraying, including specification of waiting times and need for watering of the hardening shotcrete.

2. Shotcreted drains

The drain construction studied herein is a type of long sections of single drains mounted side by side to cover tunnel lengths of up to 10–20 m. Apart from its main function, to create a dry and ice-free environment for e.g. traffic by diverging in-leaking water, a lining or wall of drains can also be used to create a protected space for tunnel installations such as ventilation, lighting and traffic control systems. This will make it possible to maintain and repair installations without interrupting traffic in the tunnel and also in some cases to inspect the inside of the drains or lining.

2.1. Long sections of drains

The drain constructions studied consists of 50 mm thick drains of polythene with a width of 1500 mm and lengths up to 5–10 m. These soft mats with closed pores are placed vertically side by side with overlaps along tunnel walls, or ceilings, as shown in Fig. 1. The drain mats are attached to the rock using ϕ20 mm rebars spaced 1200 mm, creating a void between drain and rock due to the irregular shape of the rock surface, which to some extent allows for inspection of the inner surface of the drains. The drains are first covered with a layer of steel fibre reinforced shotcrete which in turn is covered by a second, un-reinforced layer. The in all 60 mm thick shotcrete is fixed to the rock on both sides of the drain mats by bond only. It is important that the fibre content is adequate because even if the shotcrete is designed to function in the elastic state the fibres are needed to decrease the risk for fallout of shotcrete pieces in the case of overload (Holmgren, 2004).

2.2. The Southern Link tunnels

The Southern Link (Södra länken) is so far the largest highway tunnel project completed in Sweden, inaugurated in October 2004. A system with six kilometres of six-lane highway through 16.6 km of rock tunnels connects the southern parts of Stockholm. The different alternatives for collection of in-leaking water considered in the design stage were shotcrete drains, screen drainage and lining (Sturk et al., 1996). In the final design the road surface is fully protected from leaking and dripping water through prefabricated concrete elements suspended from the ceiling in rock bolts. The tunnel walls consists of shotcrete, partly covering long sections of drains but also a large number of single 1500 mm wide drains (NVF, 2008), as shown in Fig. 2. This alternative was chosen although there were uncertainties concerning the construction cost and its long-term performance, e.g. clogging and frost burst of pipes (Sturk et al., 1996). Further details on the shotcrete use in the Southern Link are given by Karlsson and Ellison (2001).

3. In situ investigation

Towards the end of construction of the Southern Link a thorough mapping was done of all the sections of the tunnels with shotcrete covered drains. The shotcrete surface was investigated

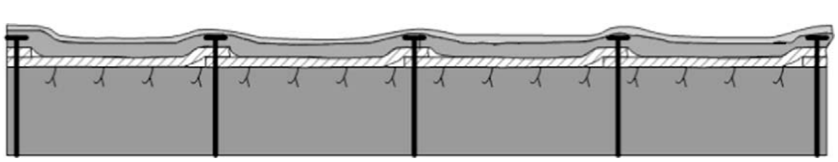

Fig. 1. Section of shotcreted drains on rock. Two layers of shotcrete and steel bolts.