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Laboratory testing of early age bond strength of shotcrete on hard rock

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ABSTRACT

This study investigates early age bond strength of shotcrete (sprayed concrete), in the case of shotcrete sprayed on hard rock. Shotcrete differs from ordinary, cast concrete through the application technique and the addition of set accelerators which give immediate stiffening. The bond between shotcrete and rock is one of the most important properties. During the very first time after spraying the physical properties and the bond to the rock depend on the set accelerator and the micro structure that is formed. In this work a laboratory test method for measuring early bond strength for very young or early age shotcrete is presented. 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.

1. Background

Early high bond strength is vital for efficient and safe shotcrete rock support during tunnelling through hard rock. For a shotcrete lining anchored with a minimum of, or no, rock bolts the ability to quickly form a strong bond to the substrate is the most important material property. If such a shotcrete lining is reinforced with e.g. fibres or steel mesh in order to gain ductile strength, large undetected areas of un-bounded shotcrete can develop as the shotcrete shell maintain its functionality as long as the rock deformations are infinitesimally small. However, already at deformations of about a few millimetres severe failures can develop due to stress concentrations. It is thus of outmost importance that the occurrence of un-bonded areas are kept to a minimum and that the design of the shotcrete lining can be based on reliable estimates of the bond strength between rock and shotcrete as function of shotcrete age.

1.1. Un-anchored shotcrete

The efficiency of an un-reinforced, un-anchored shotcrete lining was demonstrated during in situ testing of young shotcrete subjected to vibrations from blasting (Ansell, 2004). The results show that shotcrete younger than 24 h can maintain its functionality even after having been subjected to vibrations from blasting that cracked the hard rock substrate. It was concluded that bond loss was the dominant failure mode and the following evaluation of the results (Ansell, 2005, 2007) highlighted the need for accurate data on early bond strength as input for numerical analyses. Also, it was shown that the relation to strength growth for other parameters, such as modulus of elasticity and tensile strength, is important for the performance of a hardening concrete lining. The results presented in the present paper is therefore used as a basis for the finite element modelling of shotcreted tunnel walls during blasting, presented by Ahmed and Ansell (in press). Although shotcrete has the same basic material composition as ordinary cast concrete, the method of placement gives it unique material performances. The use of additives such as set accelerators and the underground climate and temperatures also affect the strength growth ratio of shotcrete. It is thus not recommendable to base numerical analysis of shotcrete performance on material properties obtained for cast concrete and this emphasizes the need for reliable material data for young and hardening shotcrete, especially for the bond strength between rock and shotcrete. For the latter there is little, or no, data published which is due to the difficulty in performing this type of tests for very young shotcrete using existing testing methods. Bond strength between shotcrete and rock is usually tested in situ using pull-out techniques, e.g. on pre-drilled cores. Mechanical cutting of the shotcrete and attachment of pull-out couplings are only possible on fully hardened shotcrete and therefore there is a need for a new testing technique that could be used also for very young shotcrete, without disturbing the bond that is to be measured. There are three main principles for testing of shotcrete bond strength

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in the direction perpendicular to the substrate, see e.g. Bryne et al. (2013). The basic test methods are schematically described in Fig. 1 where the first (a) is pull-out of cores, pre-drilled through the concrete and the outer layer of the rock. Three basic failure modes are possible; complete bond failure, shotcrete tensile failure and rock failure, or combinations of these. The method is well established for use on fully hardened shotcrete in situ and can easily be adopted for use in laboratory environment. Other drawbacks with the method, apart from the requirement of fully hardened shotcrete, are that the core drilling may cause damage to the bond at the shotcrete–rock interface and that there may be frictional resistance during the pull-out operation. The second method (b) is to pull steel discs mounted on the rock surface prior to spraying through the shotcrete lining. This method, described in detail by O'Donnell and Tannant (1997), 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. The method can, however, be used also with very young shotcrete.

1.2. Test method for young shotcrete

The third technique (c) is the basic principle for a newly developed test method, see Bryne et al. (2011) and Bryne et al. (2013). In this case the direction of pull is reversed compared to 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. The method can be used in laboratory environment or in situ, with samples shotcreted specially for testing. It is not possible to use the method with shotcrete on a rock wall since the pull-out equipment must be installed facing the direction of pull. The test set-up uses a slab of finite thickness, e.g. of granite or other rock type, on which the shotcrete is applied. The pull-out equipment is mounted on the opposite side where it is connected to pre-drilled cylindrical cores through the slab. These are mechanically fixed to the slab prior to shotcreting and the gap between core and slab are sealed to prevent it from filling during shotcreting. One surface of the cylinder thus bonds to the shotcrete while the opposite surface has a coupling device for the pull-out equipment. With proper choice of sealing material this set-up will provide a method for direct testing of the bond strength that can be used with shotcrete only a couple of hours old, without any disturbance from core drilling or frictional losses. The development of the test-setup is described by Bryne et al. (2013), also presenting results from bond strength testing obtained with cast test specimens, using mortar composition identical to shotcrete. The present paper presents results from laboratory testing of shotcreted test samples.

2. Shotcrete bond strength

The bond strength possible to obtain between shotcrete and hard rock depends on a large number of factors. Also the skill and accuracy of the operator handling the spraying equipment are of high importance. In the following conditions applicable for wet-mix shotcrete on hard rock are assumed, unless otherwise stated. The presented results are given as examples and for more details see e.g. the summary by Hahn and Holmgren (1979).

2.1. Shotcrete–rock bond

The bond strength between two materials such as shotcrete and rock depends on a large number of mechanisms, such as mechanical interlocking and adsorption (Kinloch, 1980). This bond generally follows the same principles as for other adhesives (Concrete handbook, 1994), demonstrated by the fact that shotcrete can bond to a large variety of materials, as e.g. concrete and steel. Other factors, such as the material microstructure and interface surface geometry, also contribute to the overall strength and reliability of the bond. The bond strength of shotcrete can thus be defined as the ability to adhere to a particular surface, which often is rock or concrete. The bond possible to obtain on hard rock surfaces is governed by type of rock, the condition of the surface and the method of spraying, i.e. using wet-mix or dry-mix method, see e.g. Vandewalle (1998). The mechanism of adhesion between different rock material and cement paste was evaluated in detail by Rehm et al. (1977) and from the investigations by Hahn and Holmgren (1979) it can be seen that the type of rock mineral is more important than the roughness of the rock surface. The importance of a clean rock surface has been shown by Barbo (1964) and it is also well known that free water on the rock surface will cause a significant reduction of the bond strength, see Karlsson (1980). The effect from various surface treatments, such as mechanical scaling, scaling and high-pressure water washing and water-jet scaling is demonstrated by Malmgren et al. (2005). The results show that mechanical scaling without cleaning, i.e. water spraying, and lead to a significantly higher occurrence of shotcrete areas with low or no bond strength. Also, for efficient use of wet-mix shotcrete set accelerators are used and these will, apart from accelerating the strength growth, also affect the rate of shrinkage which may lead to severe loss of bond.

2.2. In situ observations and test results

Pull-out tests of fully hardened shotcrete on hard rock usually show bond strengths within 0.5–2.0 MPa, see Holmgren (1992).

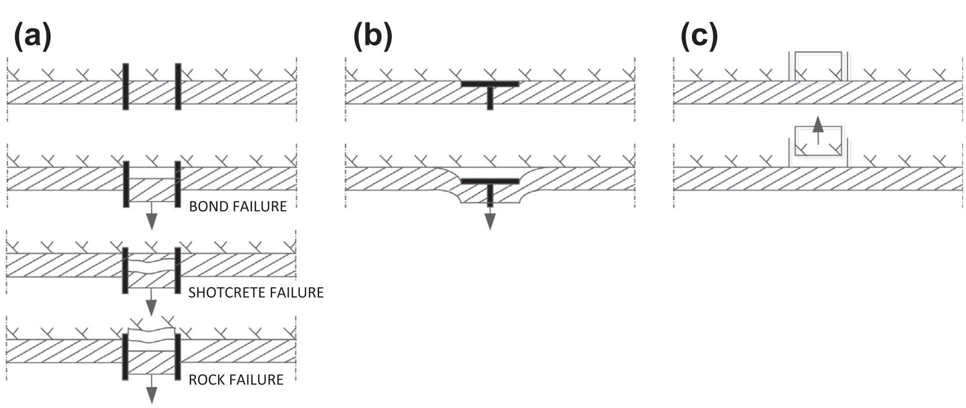

Fig. 1. Principal methods for shotcrete bond strength testing. Pull-out of drilled test cores (a), pull-out of shotcrete covered steel discs (b) and pull-out in the reversed direction of a substrate core (c). From Bryne et al. (2013).