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Laboratory tests and numerical modelling of strength-deformation parameters of a shotcrete lining

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ABSTRACT

This article describes the procedure for and results of tests of the strength-deformation parameters of unreinforced shotcrete conducted at the Central Mining Institute of Poland. The methodology of the laboratory tests and the results are presented in the form of a series of loading forces and deformations of a layer of shotcrete over time. The tests results show a strong influence of adhesion between shotcrete and rock. Numerical models were used to assess the behaviour of shotcrete-rock composite behaviour based on laboratory tests.

1. Introduction

Shotcrete is a mixture of cement, aggregates, sand, various types of additives, and water. This material is sprayed at high speed onto the exposed surface of a rock strata through a wet or dry method [7,1]. The first attempts to use shotcrete in the mining industry were conducted in the USA in 1914. The method underwent dynamic development in the 1950s. In the subsequent decades, shotcrete was used in many countries throughout the world in both civil engineering and mining [33,18,19,12]. Since the 1970s, steel fibres have been used as reinforcement in shotcrete, and polypropylene fibres recently began to be used as a substitute. The additives positively influence the deformation parameters of shotcrete and its tensile strength [10,5].

The primary advantages of a shotcrete lining are the following [33]:

– preventing the mobility of rocks in a excavation,
– creating a stress state, similar to a tri-axial state, in the rock mass around a excavation,
– developing an arch around the excavation to limit the occurrence and propagation of cracks and delamination in the rock mass,
– protecting rocks against erosion,
– securing excavations against the flow of gases and water from the rock mass,
– positively influencing the climate conditions in excavations, and
– positively influencing the ventilation of excavations through the streamlining of air flow.

Shotcrete lining is being increasingly commonly used in Polish collieries. At present, shotcrete (mainly without reinforcement) is mostly used for the reinforcement of corroded arches of steel supports, insulation of intakes of excavations with dams, reinforcement and repair of the main excavations near a shaft, insulation of fragments of roadways if they are driven through coal seams, thermal insulation of the rock mass, and separation of steel arch supports from an aggressive environment. It is estimated that approx. 90,000–100,000 m^2 of shotcrete were sprayed in Polish collieries in 2011 [25]. Of all the above-mentioned applications of shotcrete, this material is most often used for reinforcing corroded arches of steel roof supports. Due to the conditions in the excavations of collieries, particularly high air humidity and aggressive mine water, the corrosion of steel arch supports is a serious problem [26]. Fig. 1a shows an example of a corroded V profile, and Fig. 1b shows the spraying of shotcrete onto a steel arch support. In Poland, the commonly used method for applying shotcrete is the dry method. Usually, two or three layers of shotcrete are applied. The final thickness of shotcrete is between 10 and 15 cm [25].

Considering the progress made in the use of shotcrete in Polish collieries, the Central Mining Institute has initiated studies aimed at, among other goals, assessing the strength parameters of both a shotcrete lining and the shotcrete reinforcement of corroded arches [29,30]. The present article describes the methodology of

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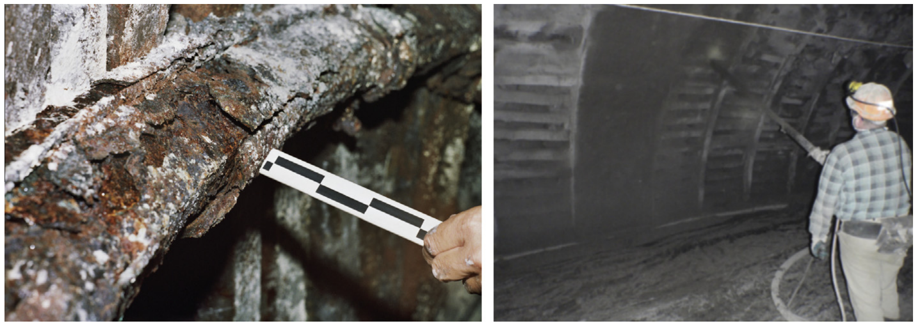

(a) (b)

Fig. 1. Use of shotcrete in polish collieries: (a) a corroded V profile, (b) spraying a layer of shotcrete on support arches [25].

the laboratory tests used to assess shotcrete through the so-called box of rocks test and presents the results of the tests in the form of a record of loading forces and deformations of a layer of shotcrete over time. Selected numerical models based on the finite element method were used to simulate the behaviour of shotcrete during the laboratory tests. The results of the calculations were compared to the record of a laboratory test. The comparison of the results of the numerical calculations with the results of the laboratory tests revealed a satisfactory level of compliance.

2. Laboratory tests of the strength-deformation parameters of shotcrete

Many methods are used to determine the strength-deformation parameters of shotcrete [13,24,11,23,22,7,20]. Huge body of work has been done to assess the parameters of fibre reinforced shotcrete panels [16,4,6,35]. Some standard tests on FRC panels are also known as ASTM C-1550. Kirsten H. A. D. used hydraulically pressurized bag to achieve uniformly distributed load on FRC panel to limit the peak effect.

The basic tests on shotcrete used in underground mining include laboratory tests of its compression strength and tensile strength and the determination of its longitudinal elasticity modulus (Young's modulus). Moreover, the adhesion of shotcrete to a given surface is often determined *in situ* through, e.g., the pull-off method. The scope of the tests of shotcrete is specified in European Standards PN-EN 14488 and Polish Standards PN-G-14100. Several shotcrete tests not covered by standards also exists. Banton et al. [3] attempted to replicate the shotcrete lining behaviour by a test that based on a steel plate that was pulled through shotcrete liner. The authors modelled shotcrete lining and checked the adhesive strength between shotcrete and rock. The authors also highlighted that neglecting the strength of shotcrete-rock composite may result in conservative design.

An additional test, which is also not mentioned in the standards but provides considerable data concerning shotcrete, is the so-called box of rocks test. The test attempts to simulate the underground conditions in which a layer of the tested lining is loaded through the rock mass. The box of rocks test is quite often performed for TSL-type elastic linings [14,31,32]. The idea of the test is presented in Fig. 2.

Based on the methodology described for TSL-type linings, a method for testing other materials with steel boxes was devised at the Central Mining Institute [27]. In this method, the samples are prepared for the tests according to a multi-stage procedure. First, a 1.0 x 1.0-m steel frame is filled with fine rock material and then compacted, and a layer of granite slabs of irregular shape is then placed on the frame. A layer of shotcrete, which is usually 5-cm thick, is then sprayed (Fig. 3a). After the shotcrete hardens, the steel box is turned over, and the tested lining is subjected to the weight of the rock material, which is additionally loaded with a hydraulic cylinder (Fig. 3b), until the tested material loses its continuity and the rock material falls out of the box. This procedure applies uniformly distributed load on the shotcrete and the peak effect is reduced. The described box of rocks tests were made on unreinforced shotcrete.

During the test, the force acts on the rock material and displaces characteristic control points on the layer of shotcrete. The displacement of a layer of shotcrete is recorded with extensometers [27]. During the test, the load and the corresponding displacement of each of the five measurement points (D-5, D-6, D-7, D-8, and D-10), the locations of which are shown in Fig. 4a, are recorded.

Within the framework of the statutory works of the Central Mining Institute [29], we conducted laboratory tests of the strength and deformation of three layers of shotcrete according to the aforementioned methodology. Fig. 5 shows the fragments of rock material within a steel frame after the tests. A layer of loose gravel, which was not bound during shotcreting, and larger fragments of granite slabs are clearly visible.

Fig. 6 shows the displacement characteristics of the lining, which are expressed in the form of a dependence of the force generated by a hydraulic cylinder loaded onto the rock material (increased by the weight of the rocks filling the box), on the displacement of the central measurement point (D-5). The adhesion and friction between rock and shotcrete played a substantial part in the post-cracking performance of the unreinforced shotcrete–rock composite.

As shown in Fig. 6, the maximum load that the tested layer of shotcrete was able to bear was 77.3 kN. The displacements of the measurement points located on the layer of shotcrete were as follows: D-5, 3.31 mm (Fig. 6); D-6, 1.90 mm; D-7, 1.55 mm; D-8, 2.12 mm; and D-10: 1.88 mm. The maximum displacement of measurement point D-5 (centre of the plate) recorded during the test, before removing the rock material, was 148.9 mm.

To obtain credible input data for numerical simulations of the deflections of shotcrete, it was necessary to conduct additional laboratory tests. We determined the following average values for the parameters of shotcrete after 37 days of hardening: Young's modulus $E = 2011$ MPa, uniaxial compression strength $f_c' = 21.7$ MPa, and tensile strength $f_t' = 1.74$ MPa.

3. Deformation and stress based on the thin plate bending theory

The deformation and distribution of stress within a layer of shotcrete can be analysed through the thin plate bending theory. A thin plate of even thickness is a body limited by two parallel planes, the distance between is much smaller than the other