Shotcrete

Shotcrete has been used for securing underground openings for many years—one might say not entirely adequately. Ordinary applied shotcrete has a tensile strength of 2–3 MPa, while higher-quality shotcrete can achieve tensile strength of 4–5 MPa, naturally after 28 days. This is the tensile strength of medium-strong rocks. Shotcrete reinforced with fiber shows negligible increases in tensile strength. Fibers are wire pieces made of steel or other materials, with diameters under 1 mm and lengths 50 times greater.

Applied shotcrete is not a material but a support structure. As already explained in previous texts, the direction of the maximum principal stresses—both in the rock and in the applied shotcrete—is parallel to the wall of the underground opening, and the minimum principal stresses are perpendicular to the wall of the opening (the free surface). The maximum principal stresses cause tension, and the minimum principal stresses oppose it.

When the tensile stress exceeds the tensile strength, cracks appear, which are perpendicular to the direction of the minimum principal stresses. In other words, the limit state of the structure can be described by the formula:

$$\sigma_{td} + \sigma_3 = st \cdot \sigma_1$$

The minimum principal stresses are determined by the initial stress state and the shape of the underground opening, while the tensile strength of the shotcrete (concrete) in the direction of the minimum principal stresses (σ_td) is the same in all directions in ordinary shotcrete. In shotcrete reinforced with steel fibers, the tensile strength is increased by the tensile strength of the fibers, but only in the direction of the embedded steel wires. It is easy to conclude—and can be verified—that due to the method of shotcrete application, the wires are embedded in the direction perpendicular to the one required.

Such embedded fibers affect the change in internal friction angle and Poisson's ratio of the composite material (concrete + fiber). They also affect the increase in the tensile strength of the structure—but in the direction in which the structure is loaded in compression.

This can be overcome in at least two ways:

The first method is embedding fibers made of bent steel wire, which ensures that in every case there are parts of the "reinforcement" positioned in the direction of the minimum principal stresses. Figure 1 provides an illustration of the concept with two proposed solutions.

Figure 1. Proposed shapes of fiber reinforcement

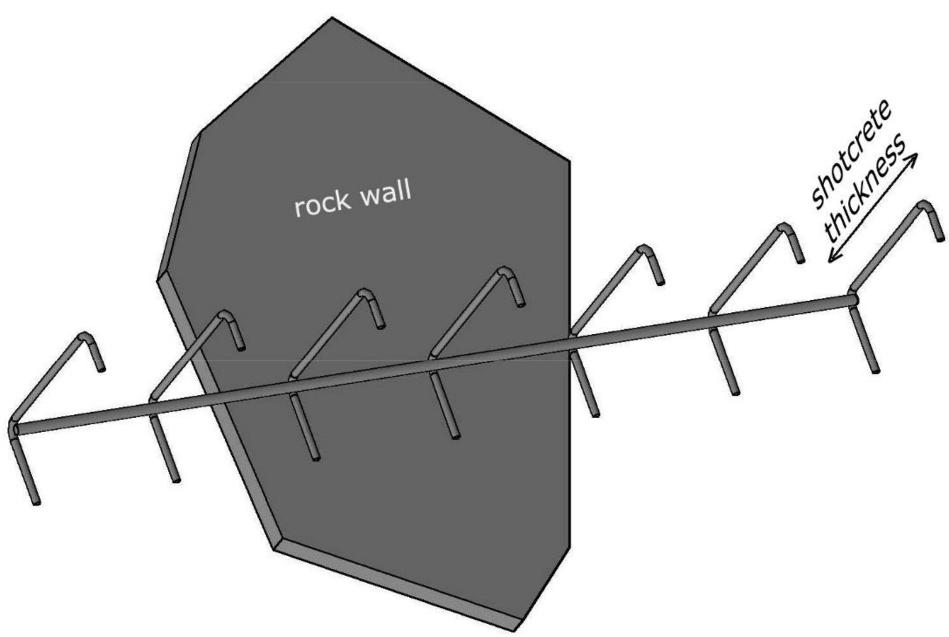

Figure 2. Reinforcing shotcrete

The second proposed method is installing prepared steel reinforcement segments on the wall of the opening before applying the shotcrete, as shown in Figure 2. Prepared reinforcement segments made of rebar are mounted to the rock wall. The segments are glued or "pinned" to the wall, fastened with shallow anchors. The length of the load-bearing part of the reinforcement is equal to the thickness of the shotcrete. An auxiliary rebar holds the bearing bars in the required position. The thickness and number of bearing rebars depend on the required tensile strength of the composite (concrete + steel) in the appropriate direction.

Shotcrete installed in this way can completely replace more expensive cast concrete lining. If sensors are installed, the stress in the applied lining can be monitored, and a new layer of shotcrete with appropriate tensile strength in the direction of the minimum principal stresses can be added in time.

Tensile strength is regulated by the appropriate amount of steel. With good monitoring and timely response, most failures in preparatory and transport drifts in the mining zone, for example, can be prevented.