Exploring the Limits of Shotcrete Loading Capacity at Early Age

by Matthew Clements

The booming world mineral market is introducing a new level of challenges to miners as they strive for higher productivity in an attempt to maximize return from record metal prices. In underground Australian mines producing gold, nickel, copper, lead, silver, and zinc, fiber-reinforced shotcrete has become the favored ground support due to productivity advantages. The ability to reenter a shotcreted heading as soon as is safely possible after shotcrete has been applied is a critical factor to the production cycle time achieved.

Fig. 1: Remote in-cycle shotcrete application

A typical excavation cycle consists of drilling the face, charging up with explosives, firing, mucking out, shotcreting, and bolting. Shotcrete has replaced the traditional mesh and bolt approach as it has speed advantages, provides a higher level of support, and eliminates much of the rehabilitation work that is required later in meshed areas. Although the direct costs of installing shotcrete are greater than the cost of the meshing, the time savings easily make the shotcrete worthwhile.

The shotcreting cycle consists of applying the shotcrete and waiting for it to cure. The application is undertaken by a remotely-controlled shotcrete machine (Fig. 1) with a single operator who typically applies the 3 to 3.8 yd^3 (4 to 5 m^3) required in each heading in approximately 30 minutes plus setup time.

The curing time is the time taken for the shotcrete to reach a strength that is designated by the mine as sufficient to allow the safe reentry of personnel beneath the green shotcrete. Typically, the next activity involves installing rock bolts through the shotcrete layer. As this task can be achieved remotely from behind the last row of bolts, this activity can commence before the shotcrete is fully cured. This means there are effectively two critical points:

1. When the shotcrete is strong enough to allow bolting without damaging the shotcrete layer; and
2. When the bolted shotcrete layer is strong enough to be designated safe for personnel reentry.

The shotcrete in-place strength is measured by using a penetrometer of the type shown in Fig. 2. This is known as a Meyco Needle Penetrometer. The resistance to the needle being pushed a set distance into the shotcrete layer is measured and calibrated to the shotcrete compressive strength. Note that other types of penetrometers may not be reliable and should be calibrated before being relied on as a compressive strength estimating tool.

Fig. 2: Early strength test with a Meyco Penetrometer

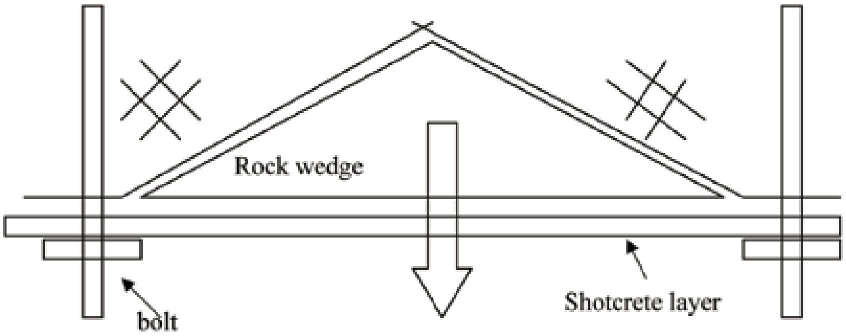

Fig. 3: Typical rock wedge failure that relies on safe shotcrete support


Fig. 4: Pull-out disc mounted ready to receive shotcrete

The questions that arise from all this are:

1. What strength is required before remote bolting can safely begin? and
2. What strength is required before it is safe for personnel reentry?

The first question is relatively easy to answer. Bolt installation by a robotic drilling jumbo uses a compressed air drill and water flushing. The compressed air and water can damage a very green shotcrete layer. By some experimentation, it is seen that a compressive strength of 87 psi (0.6 MPa) will prevent this from occurring. A tell-tale sign of bolting being undertaken too early is when the bolt plates can be seen to be pulled into the shotcrete layer when the bolts are being fastened. This damages the shotcrete layer at a critical point and must be avoided.

The second question involves determining the ultimate loading capacity of shotcrete at a very early age and is very difficult to determine. This question has consumed a fair amount of research and analysis in Australia in recent times. To analyze what is required, let us take a typical loading situation in a shotcreted face.

The critical factors are the size and weight of the rock wedge and the thickness and strength of the shotcrete layer spanning between the two bolts. The strength of the shotcrete layer will depend on a combination of its compressive strength, shear strength, flexural strength, and adhesion to the rock face. It is not immediately clear which failure mode will dominate the behavior at a given point in time. To investigate this, Grenz Consulting (Principal Matthew Clements) and Technologies in Structural Engineering (Principal Stefan Bernard) set up a series of experiments. The experiments were sponsored by mining company BHP Billiton. The experiments were initially aimed at reliably predicting which failure mode was dominant in early-age capacity failures. Once this was solved, the task then became to predict the loads that the shotcrete layer could safely sustain within the first few hours after application.

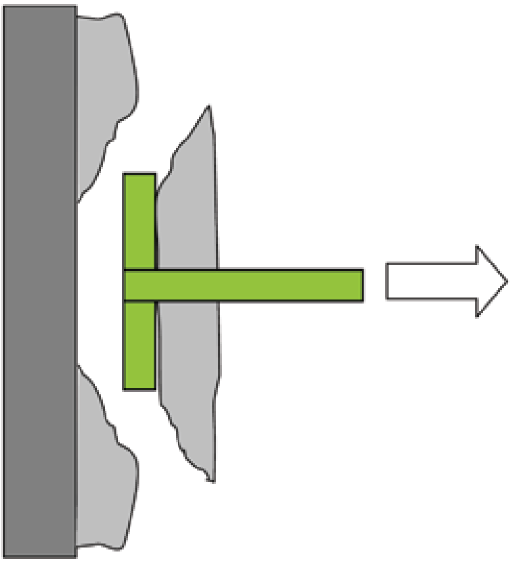
Fig. 5: Shear failure of shotcrete

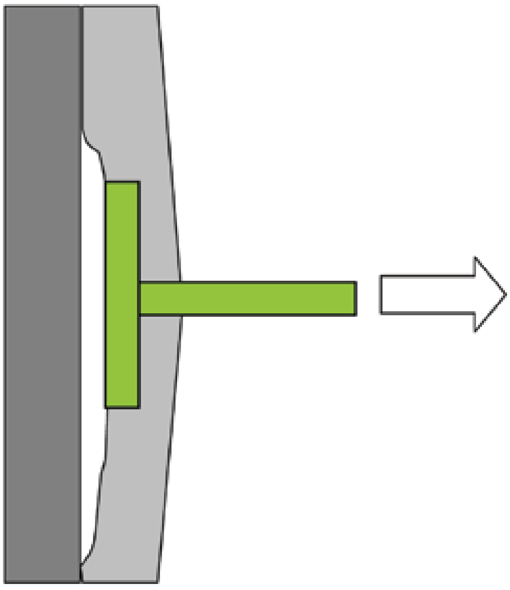
Fig. 6: Adhesion failure of bond followed by flexural bending failure of shotcrete

The experimental methodology involved mounting steel discs onto a wall surface (refer to Fig. 4) and spraying a layer of fiber-reinforced shotcrete over the discs. The discs are then pulled through the shotcrete layer at various times covering the first few hours after application. The force required to pull the discs until the liningfails are measured and the mode of failure observed. This is correlated against the compressive strength of the shotcrete.

In stage one of the experiments, the discs were mounted onto the wall of a concrete culvert and covered with 2 in. (50 mm) of fiber-reinforced shotcrete. The compressive strength of the shotcrete was checked regularly using several techniques including the Meyco Penetrometer (refer to Fig. 2). The first testing took place when the shotcrete was only 44 psi (0.3 MPa) and occurred within the first hour. It could clearly be observed that at very early ages the shotcrete layer failed in shear, but later, as the shotcrete strengthened, the failure mode changed to a bending failure.

The decisive moment when the failure mode changes from shear to flexural bending occurs when the tensile stress around the load point exceeds the adhesive strength. This is a critical observation.

Once this mechanism was understood, the testing moved to rock faces in underground mines. Pull-out discs are mounted on the rock face as shown in Fig. 7. A 2 in. (50 mm) layer of fiber-reinforced shotcrete is sprayed over the wall. The discs are then pulled out through the shotcrete layer with a hydraulic jacking arrangement that measures the force and displacement (refer to Fig. 8).

It is important to understand the role that adhesion plays in determining the failure mode. Adhesion occurs instantly when shotcrete is sprayed onto the rock face and dominates the early strength behavior. Adhesion grows slowly as compressive strength increases. Some time within the first 24 hours, the concrete strength increases to a point where the failure mode changes to flexural bending. This can be seen when the shotcrete layer under load starts to debond from the rock face before failing. This induces a flexural bending failure as shown in Fig. 9. Up until that point, the failure mode is always in shear. Adhesion strength tests were conducted simultaneously to the pull-out tests.

The test produces a load-displacement curve as shown in Fig. 9. Typically, a peak load is reached as the first crack occurs. The curves with flat tops (tests 5 through 10) indicate debonding occurring, and these tests are exhibiting flexural bending failures. Tests 1 through 4, which are taken at earlier ages, all induced shear failures. The shear capacity of the shotcrete layer can be calculated from the peak load measurements. Once we have the shear capacity, we can undertake the necessary calculations to predict the rock load that can be safely carried by the shotcrete layer.

The calculated rock load depends on the shotcrete to rock adhesion, the shotcrete strength, and shotcrete thickness. The result cannot be generalized and must be experimentally determined at each mine site. Many mines in Australia are currently carrying out these tests to determine their safe reentry times into shotcreted headings. Once a safe shear load capacity has been established, the shear strength is able to be estimated at the shotcrete face from the compressive strength as measured by the Meyco Penetrometer.

This type of research is allowing underground mines to safely use fiber-reinforced shotcrete to its maximum potential in the race for productivity.

Fig. 7: Pull-out discs in underground mine

Fig. 8: Hydraulic jacking arrangement

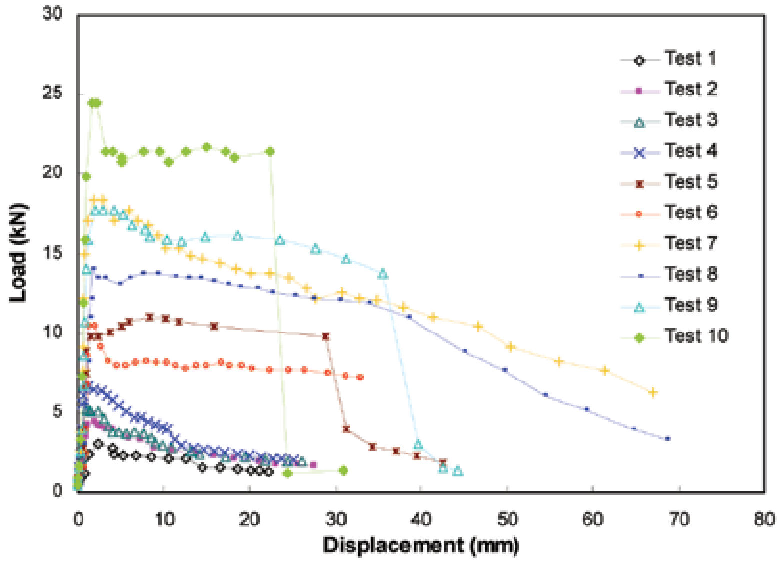

Fig. 9: Load-displacement curve from pull-out tests

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