Energy-absorbing capacity of reinforced shotcrete, with reference to the containment of rockburst damage

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Synopsis

The paper reports on loading tests conducted on shotcrete reinforced with mesh and various types of steel fibre, and compares the results with the energy-absorbing capacities of 16 mm rebar shepherd's crooks.

It is concluded that mesh-reinforced shotcrete has sufficient energy-absorbing capacity to contain rockbursts of significant magnitude, having greater energy-absorbing capability, even at a thickness of 50 mm, than 16 mm rebar shepherd's crooks. Fibre-reinforced shotcrete has energy-absorbing capabilities of the same order as, or better than, those of 16 mm rebar shepherd's crooks, but its performance is erratic.

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 SA ISSN 0038-223X/3.00 + 0.00. Paper first received Sep. 1994 and accepted Jan. 1995.

Introduction

Rockburst damage in a tunnel commonly involves the ejection of rock at high velocity from the surfaces of the tunnel. It has been observed[1] that a thickness of ejected rock of the order of 1 m is typical. Estimates of ejection velocity were given by Jager *et al.*[2] as up to 6 m/s. Ortlepp[3] estimated velocities of between 8 m/s and in excess of 50 m/s from observations in three rockbursts. The ejection of a thickness of rock of 1 m at a velocity of between 5 and 10 m/s is therefore suggested as a reasonable assumption for the design of rockburst support. The design criterion is, simply, that the density and load-displacement characteristic of the support should be such that it possesses sufficient energy-absorption capability to dissipate, within an acceptably small amount of deformation, the total energy generated by the anticipated thickness of rock moving at the estimated likely ejection velocity.

Support commonly used in South African gold mines consists of retaining elements such as rockbolts, and containing elements such as wire mesh, mesh-reinforced shotcrete, and wire-rope lacing.

Since the damage resulting from a severe rockburst involves the disruption or violent displacement of a metre or more of rock at initial velocities of several metres per second, it is necessary for the support to be able to absorb energy of the order of 100 kJ/m^2. To achieve this, it is essential that the retainment support should have specially engineered yielding capability, and that the containment support should have commensurate strength and compliance.

Capacity of Retainment Support Elements

The most commonly used retainment support elements in South African gold mines are fully grouted shepherd's crooks, made from deformed steel reinforcing bar of 16 mm diameter, the steel having an ultimate tensile strength of about 570 MPa. If it is assumed that the grout bond fails for 50 mm on either side of a separation surface, the energy-absorbing capacity of one of these elements is about 1,4 kJ. Spaced at 1 m centres, their energy-absorbing capability is 70 times less than the design energy suggested earlier.

Ortlepp[4] has demonstrated the inadequacy of these elements under rockburst conditions. From observations of damage after rockbursts, it is clear that a well-grouted rebar probably has even less of its length exposed to ductile elongation than the 50 mm assumed above, and failures of rebars in a brittle fashion have been observed. The energy-absorbing capacity in practice is therefore probably less than 1,4 kJ per element. The observation[5] that many kilometres of tunnel are damaged per year in the mining industry confirms the inadequacy of the tunnel support commonly used.

In contrast, the effectiveness of yielding cone bolts in absorbing energy has been demonstrated[4] to be more than twenty times that of a shepherd's crook. Moreover, the cone bolt has proved to be unbreakable under tensile loading up to the highest velocity of 20 m/s measured during dynamic testing.

Capacity of Containment Support Elements

From observations of performance under conditions of both static and rockburst loading, it is known that chain-link (diamond) mesh is very effective as a containment medium. Static testing of the yield characteristics of several types of wire mesh was carried out by Ortlepp[6]. Interpretation of the results of these tests on galvanized diamond mesh showed that the energy-absorbing capacity of the mesh in the test was about 1,4 kJ/m^2. This is probably greater than would be achieved in practice, since the mesh support conditions in the test were continuous around the perimeter of an area of about 1 m^2, in contrast to the discrete point support provided by rockbolts and face plates in practice. No dynamic testing of mesh appears to have been carried out.

Dynamic tests of the capacity of shotcrete reinforced with weldmesh and steel fibres have been reported by Tannant *et al.*[7]. In these tests, blasts were used to induce ejection velocities, and the velocities were measured at the surface of the shotcrete by geophones. The shotcrete generally withstood ejection velocities of 1 to 2 m/s, but failed for velocities in excess of 3 m/s (less in one case).

Ortlepp[6] carried out static *in situ* testing of shotcrete reinforced with diamond-wire mesh and loaded by a uniformly distributed pressure. This test measured loads and deflections to the stage where, at a central deflection of 0,025 m over a base length of about 1 m, the shotcrete had become cracked but remained coherent. The pressure applied reached a maximum of 550 kPa at about half the maximum deflection, and the corresponding average energy absorbed was about 0,8 kJ/m^2. However, the test was not carried to ultimate failure, and the total energy capacity would have been greater than this value.

Static tests, to large deflections, on shotcrete panels reinforced with mesh and steel-fibre that were carried out recently[8–10] showed that reinforced shotcrete continues to carry substantial load even after significant cracking has occurred.

The tests involved both point and uniformly distributed loading of 1600 mm square reinforced-shotcrete panels[8–10]. The panels were reinforced with chain-link (diamond) wire mesh, and with Dramix and Melt Extract steel fibres. The panels were retained by four bolts on a spacing of 1 m, and loading took place on the 1 m^2 area defined by the bolts.

The results from the panels tested under uniformly distributed loads were re-analysed to determine their energy content. Based on the results of the first series of tests[8], all the load-deformation curves were extrapolated to a deformation of 150 mm. It was then assumed that the load capacity decreased to zero at a deformation of 200 mm. A good example of one of the curves is shown in Figure 1.

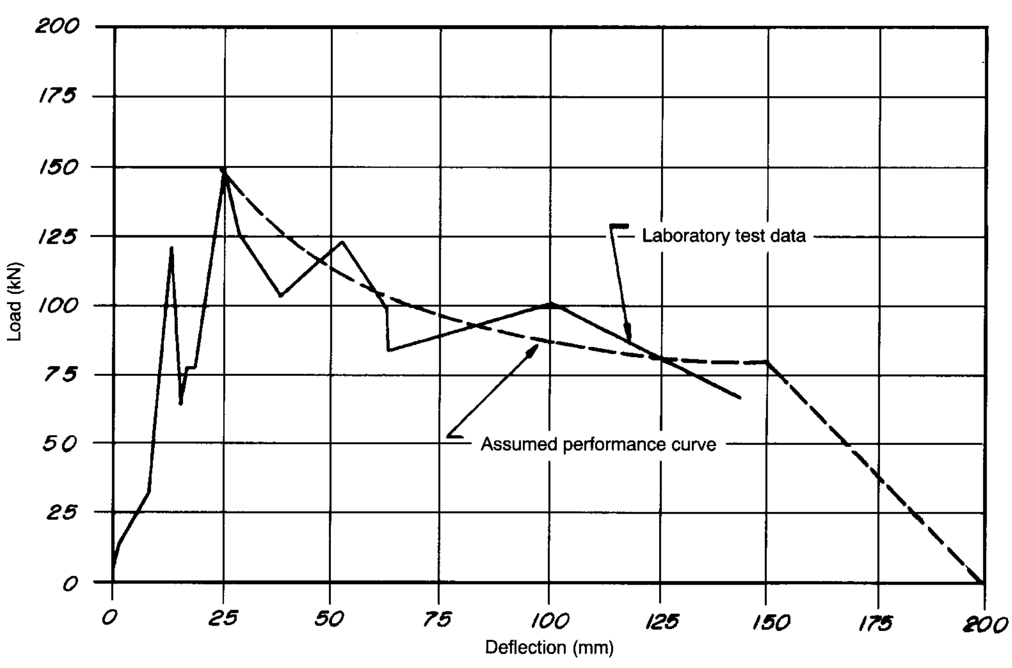

Figure 1—Load–deformation curve for 100 mm thick mesh-reinforced shotcrete

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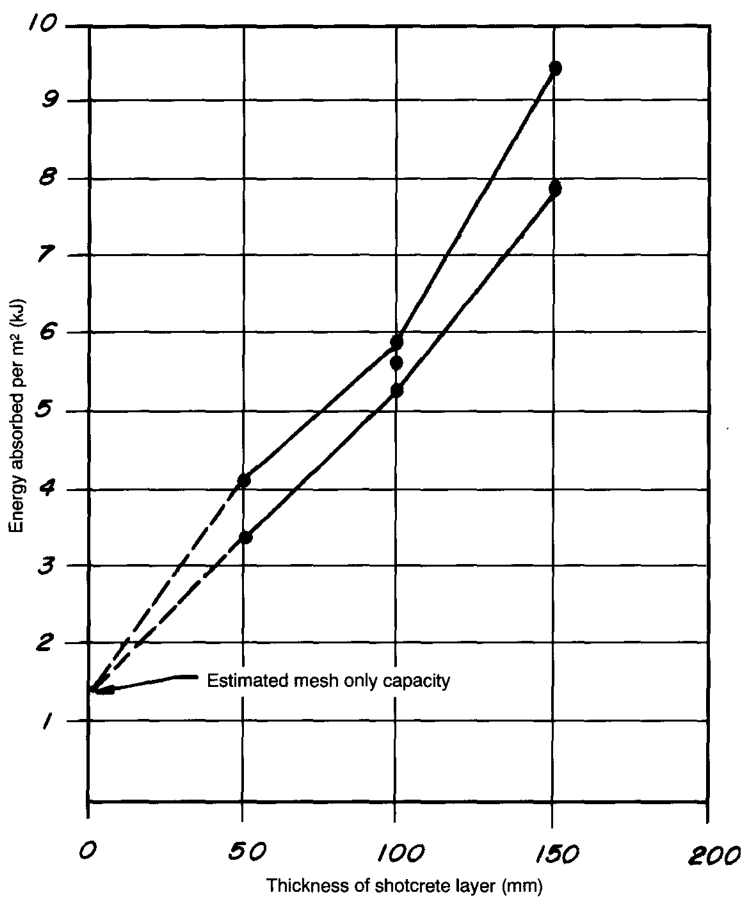

Figure 2—Energy-absorbing capacity of mesh-reinforced shotcrete

Table I

Results for the shotcrete panels

Thickness of shotcrete mm	Energy absorbed kJ	Steel content by weight %	Type of steel	Length of fibre mm
50	4,09	2,67	Dramix	30
50	1,70	1,38	Dramix	30
50	1,15	1,57	Melt Extract	25
50	2,02	1,37	Melt Extract	35
50	1,09	0,70	Melt Extract	30
50	4,17	1,42	Wire mesh	–
50	3,47	1,42	Wire mesh	–
100	4,72	2,60	Dramix	30
100	2,16	1,47	Dramix	30
100	5,71	1,22	Melt Extract	35
100	2,89	0,61	Melt Extract	50
100	3,59	0,60	Melt Extract	50
100	5,92	0,71	Wire mesh	–
100	5,70	0,71	Wire mesh	–
100	5,28	0,71	Wire mesh	–
150	10,9	2,63	Dramix	30
150	22,5	1,15	Melt Extract	35
150	5,81	0,63	Melt Extract	50
150	9,55	0,47	Wire mesh	–
150	7,93	0,47	Wire mesh	–

The areas under the curves were measured to give the total energy content. In the determination of the average energy absorbed, it was assumed that the geometry of the panel deformation was pyramidal, and the total energy was divided by 3 to give the average value. This assumption is supported by the deformation and failure behaviour of the panels[8–10].

Figure 2 summarizes the energy-absorbing capabilities of mesh-reinforced shotcrete. It appears from this figure that the mesh reinforcement produces a uniform behaviour. In contrast, the results for fibre-reinforced shotcrete showed a lot of scatter in performance, probably owing to the variation in fibre content, and possibly also to the distribution of fibres, in the panels. The results (Table I) indicate that all the panels, including the fibre-reinforced panels, have energy-absorbing capacities of the order of, or greater than, conventional 16 mm rebar shepherd's crooks.

With reference to the shotcrete reinforced with wire mesh, the typical average energy-absorbing capacities are about 4 kJ/m^2, 5,5 kJ/m^2, and 9 kJ/m^2 respectively for shotcrete layers of 50 mm, 100 mm, and 150 mm thickness. If it is assumed that the shotcrete will perform equally well under dynamic conditions, then, for an ejected thickness of rock of 1 m, these correspond to ejection velocities of about 2 m/s, 2,3 m/s, and 3 m/s respectively. These are well below the design value recommended earlier. Jager and Roberts[11] suggest that velocities of 3 m/s rarely occur outside the immediate source area, and that velocities of over 2 m/s are relatively uncommon. If this is the case, mesh-reinforced shotcrete would be very effective in containing rockburst damage in a significant number of cases, provided that some tendon reinforcement in the rock prevents dislodgement of blocks or slabs of large dimension. The addition of wire-rope lacing is likely to considerably increase the energy-absorbing capacity of containment support. However, no performance data on the extent of this likely increase are available.

An additional effect of shotcrete is considered to be the confinement it provides to the rock mass. This promotes close contact and friction between rock blocks and slabs, enhancing the energy-absorbing capability of the rock mass itself during deformation.

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It should be noted that even the 50 mm shotcrete thickness has much greater energy-absorbing capacity than conventional shepherd's crooks. Consequently, it is likely that, during a rockburst, non-yielding retainment support will fail first and that a 'curtain' of containment support may remain, displaced but more or less intact. This behaviour has been observed in practice. The capacity of shotcrete, when compared with that of shepherd's crooks, probably also explains why shotcrete is seen to 'work' when applied in South African gold mines.

An important concept in the design of support for rockburst conditions is that the capacities of retainment and containment support components are **matched**. Owing to this need for balance, there is very little to be gained from the use of high-quality shotcrete and mesh with fully grouted rebars as retaining tendons. Even poor-quality shotcrete on its own is likely to possess equivalent energy-absorbing capacity. To provide the most effective support against severe rock-bursts, it is thus essential to use yielding retainment elements with adequate energy-absorbing capacity, together with balanced or matched containment support with similar energy-absorbing characteristics. The capacities of connection elements between retainment and containment support must also be **matched**.

The cost of providing improved 'rockburst' support is not high. By the installation of yielding bolts with a spacing slightly greater than that currently used with conventional 'stiff' grouted rebar systems, it is possible to decrease the total support cost whilst achieving substantially improved energy-absorbing capacity, as well as a probable improvement in effectiveness against rockbursts.

Conclusions

Based on the results of static tests conducted on shotcrete reinforced with wire mesh and steel fibres, the following conclusions can be drawn if it is assumed that the performance under dynamic conditions is similar to that under static conditions.

- Mesh-reinforced shotcrete has sufficient energy-absorbing capacity to contain rockbursts of significant magnitude.
- Even a 50 mm thick mesh-reinforced shotcrete layer has greater energy-absorbing capability than fully-grouted 16 mm rebar shepherd's crooks.
- Fibre-reinforced shotcrete has energy-absorbing capabilities of the same order as, or better than, those of 16 mm rebar shepherd's crooks. However, the performance of fibre-reinforced shotcrete is erratic.

The dynamic testing of containment support should be carried out to confirm the above conclusions and to determine the energy-absorbing capacity of rope lacing. ◆

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The C^2 Meter is a metallurgical instrument that provides continuous on-line measurement and control of the carbon concentration in carbon-in-pulp (CIP) and CIL adsorption tanks, thereby optimizing the gold recovery.

Accurate control measures are increasingly becoming part of the recovery process on gold plants, with Vaal Reefs having opted for a similar carbon-management system last year. ◆

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