Tunnel surface support—capacities of various types of wire mesh and shotcrete under dynamic loading

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Synopsis

The paper deals with the results of dynamic tests carried out on a range of surface support liners consisting of combinations of mesh (various types), shotcrete, and wire rope lacing. The testing was carried out over the period 1993 to 1998. The dynamic testing method made use of drop weight impact loading of test samples which attempted to simulate realistic *in situ* conditions, and the range of loading imposed was equivalent to small to severe rockburst conditions.

The results of the testing provide quantitative data, in the form of input energy, which is relevant for support design and for the choice of support types appropriate for situations in which significant mine-induced seismicity occurs or is expected to occur. In addition to the wire mesh and shotcrete liner systems tested, estimates of energy capacity are made for other, untested, systems.

Introduction

Underground mining is progressing to greater depths in many countries in the world. Mining at depths of around 3000 m is already common in the South African gold mines, and research is being carried out to investigate the problems associated with mining to depths of 5000 m. Even at shallower depths than these, damaging seismicity frequently occurs. In some cases this may be due to the fact that high horizontal stresses occur, often several times higher than the overburden stress. Such conditions are well known in Western Australia. Seismicity can cause rockbursts which result in dynamic loading of rock support elements. Rockbursts manifest as the violent ejection of rock from any of the surfaces of tunnels, and often in very localized areas. It has been observed that about a metre thickness of rock may be ejected, and that ejection velocities can be up to about 10 m/s (Ortlepp and Stacey, 1994). Figure 1 illustrates typical damage that is observed in a tunnel rockburst event. In such situations, in which failure of rock cannot be prevented, the important requirement is that the failure is contained sufficiently to maintain safety, and to ensure that the tunnels remain serviceable. Therefore, the tunnel support must be capable of maintaining its load-carrying capacity even after large movements of the walls have occurred.

Various types of wire mesh and shotcrete have been used for rock support for many years. Various test programmes to determine the static capacity of such containment support have been carried out recently (Thompson and Windsor, 1999; Tannant, 1997; Kirsten and Labrum, 1990; Kirsten, 1993). However, there is little quantitative knowledge available regarding the dynamic behaviour of such support. Research into the behaviour of various types of containment support has been carried out over a period of more than five years. This involved large-scale laboratory testing of the support subjected to impact dynamic loading imposed by a drop weight. The materials tested included:

- welded wire mesh
- diamond (chain link) wire mesh
- various types of special wire mesh
- some of the above with wire rope lacing
- special wire mesh with yielding wire rope lacing
- shotcrete
- shotcrete reinforced with welded wire mesh
- Dramix and monofilament polypropylene fibre reinforced shotcrete
- Monofilament polypropylene fibre reinforced shotcrete with wire rope lacing.

Recently, considerable interest has been shown in the use of thin membranes, or 'superskins', for rock support. All of the above support types are a type of membrane, or combinations of more than one type of membrane. Stacey (2001) has suggested that a

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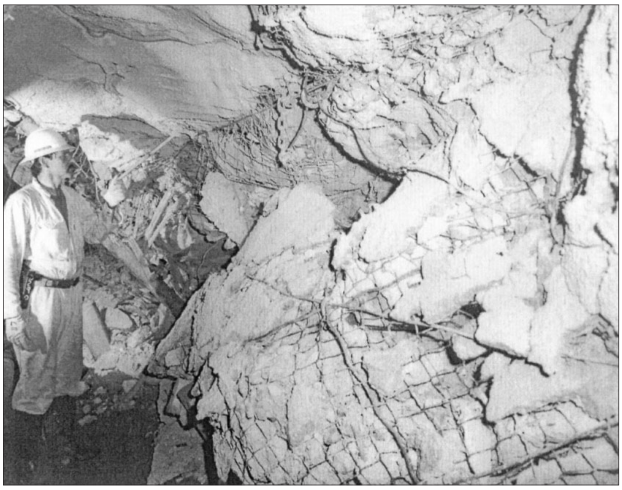

Figure 1—Support behaviour in a rockburst

single membrane should be referred to as a 'membrane component', and a combination of membrane components as a 'membrane system'.

In this paper, the test method used for the dynamic testing of membranes, and the membrane materials tested, are described briefly. The results of the tests are summarized and quantitative data provided on the capacities of the above membrane components and membrane systems. In addition, estimates of likely capacities of other (untested) membrane systems are made, based on the experience gained from the programme of research.

Test method

In developing a test method for dynamic loading of membranes, it was considered important to simulate the loading imposed during a rockburst event as realistically as possible. In a tunnel rockburst event the dynamic loading imposed on membrane support is in the form of a violent impact by the rock mass, distributed across the surface of the membrane. In this form of loading, the retainment elements consisting of rockbolts and face plates, the membrane itself, and the fractured rock mass surrounding the tunnel (provided the integrity of the fractured pieces is maintained) all contribute to the support resistance. Therefore, in an attempt to simulate rockburst loading realistically, it was considered important to take all of these aspects into account. Conceptually, therefore, the test facility had to include:

- dynamic 'impact' loading
- membrane components and membrane systems retained by rockbolts
- distribution of load onto the containment support through a 'fractured rock mass'
- a 'rock mass' which would participate in the loading and deformation
- a large area of support, to take into account the areal continuity of containment support.

The constructed test facility, which has been described by Ortlepp and Stacey (1996) and is shown in Figure 2, had the following features:

- the membrane component or membrane system was hung from support beams by four rockbolts spaced 1 m apart
- the size of the membrane 'sample' or panel was 1.6 m × 1.6 m, with the result that there was a 0.3 m overlap beyond the rockbolt support on all sides of the panel
- anchors, grouted into the ground surface, provided points of attachment for wire ropes. These provided effective extension of the boundary conditions of the test in an attempt to account for the continuous nature of membrane support. The lack of such 'extended' boundaries in the static test methods of Tannant *et al.* (1997) and Thompson and Windsor (1999) is considered to be a drawback of those test methods
- a simulated 'rock mass', consisting of three layers of 250 mm × 250 mm concrete blocks 100 mm thick, was laid onto, and in direct contact with, the membrane
- dynamic loading was provided by drop weights. Two drop weights, with masses of 1050 kg and 2700 kg respectively, were used
- the drop weight impacted onto a 40 mm thick steel impact plate, and the impact load was distributed onto the 'rock mass' by a load distribution pyramid consisting of three layers of steel-encased concrete blocks
- a maximum impact velocity of 8,1 m/s was possible, corresponding with a drop height of 3,3 m
- a maximum energy input of approximately 70 kJ/m^2 was achievable.

This test method is substantially different from that used by Tannant *et al.* (1996). It was recognized that, in a test facility incorporating the above concepts, although it would be easy to determine the total energy input, it would not be possible to define the portion of that energy actually imposed on the membranes themselves. However, in the *in situ* condition, much of the dynamic energy is consumed in such areas as acceleration of the rock, friction between rock blocks, creation of new fractures, heat, etc. Therefore, it is argued that the quantification of the capacities of membranes (energy absorption and deformation) in terms of input energy is realistic. The method described above has allowed a series of tests with repeatable loading conditions to be carried

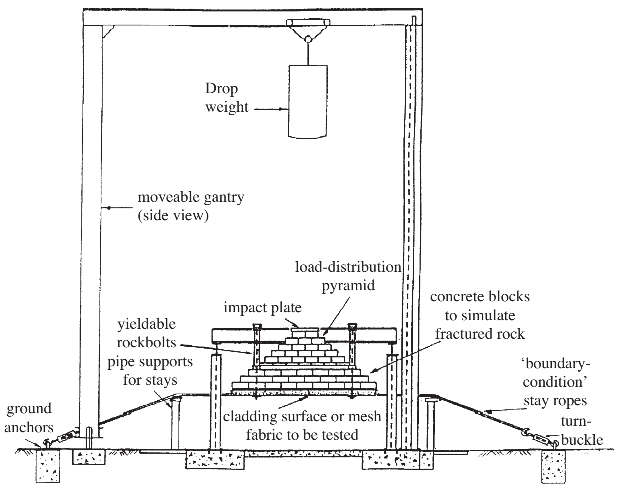

Figure 2—Dynamic test loading facility

out. This has allowed the comparative performance of membranes to be determined, and the input energies and corresponding deformations to be quantified.

Membrane materials

The membrane materials tested in the programme of research were those commonly used in the South African mining industry. The membrane components and membrane systems tested have been listed in the first section. The characteristics of the membrane materials were as follows:

- the apertures and strand diameters of the weld mesh used were 100 mm x 3.5 mm and 100 mm x 4 mm
- the apertures and strand diameters for the diamond meshes were 75 mm x 3.2 mm, 100 mm x 3.2 mm and 100 mm x 4 mm
- special meshes included commercially available high yield meshes, and conventional weld meshes modified to introduce yield capability
- wire rope lacing with diameters of 8 mm, 10 mm and 12 mm was used
- friction yield loops were introduced into the wire rope lacing component in two tests
- shotcrete had a nominal strength of 25 MPa and was sprayed with a nominal thickness of 75 mm. However, within each shotcrete panel, thicknesses varied between about 70 mm and 120 mm
- wire mesh reinforcement in shotcrete was welded wire mesh with a 100 mm aperture and 4 mm strand diameter
- fibre reinforcement in shotcrete consisted of 30 mm long Dramix fibres, and 40 mm long monofilament polypropylene fibres.

Test results

The results of the programme of research are summarized in Figure 3, in which they are plotted in terms of centre deflection of the panel against the total input energy. It can be seen that unreinforced shotcrete has the poorest performance, and that weld mesh also occupies the lower energy area of the plot. Strands of the weld mesh broke in almost all of the tests, and in some cases welds broke as well. It was found that the sharp-edged steel face plate contributed to the failure of the strands.

Diamond mesh performed better than the weld mesh. However, there was a tendency for this mesh to unravel once a single wire strand had failed, and this allowed the 'rock mass' to spill through.

The performance of fibre-reinforced shotcrete was approximately equivalent to that of diamond mesh. Shotcrete reinforced with Dramix steel fibres performed slightly better than that with monofilament polypropylene fibres. A concern with regard to the performance of fibre reinforced shotcrete, indicated from the testing is that, after the initial weight drop, which was contained by the shotcrete membrane, a second drop on the same panel destroyed the panel. The implication is that the effectiveness of fibre-reinforced shotcrete as a membrane component on its own may be questionable if subjected to repeated dynamic loading, or to

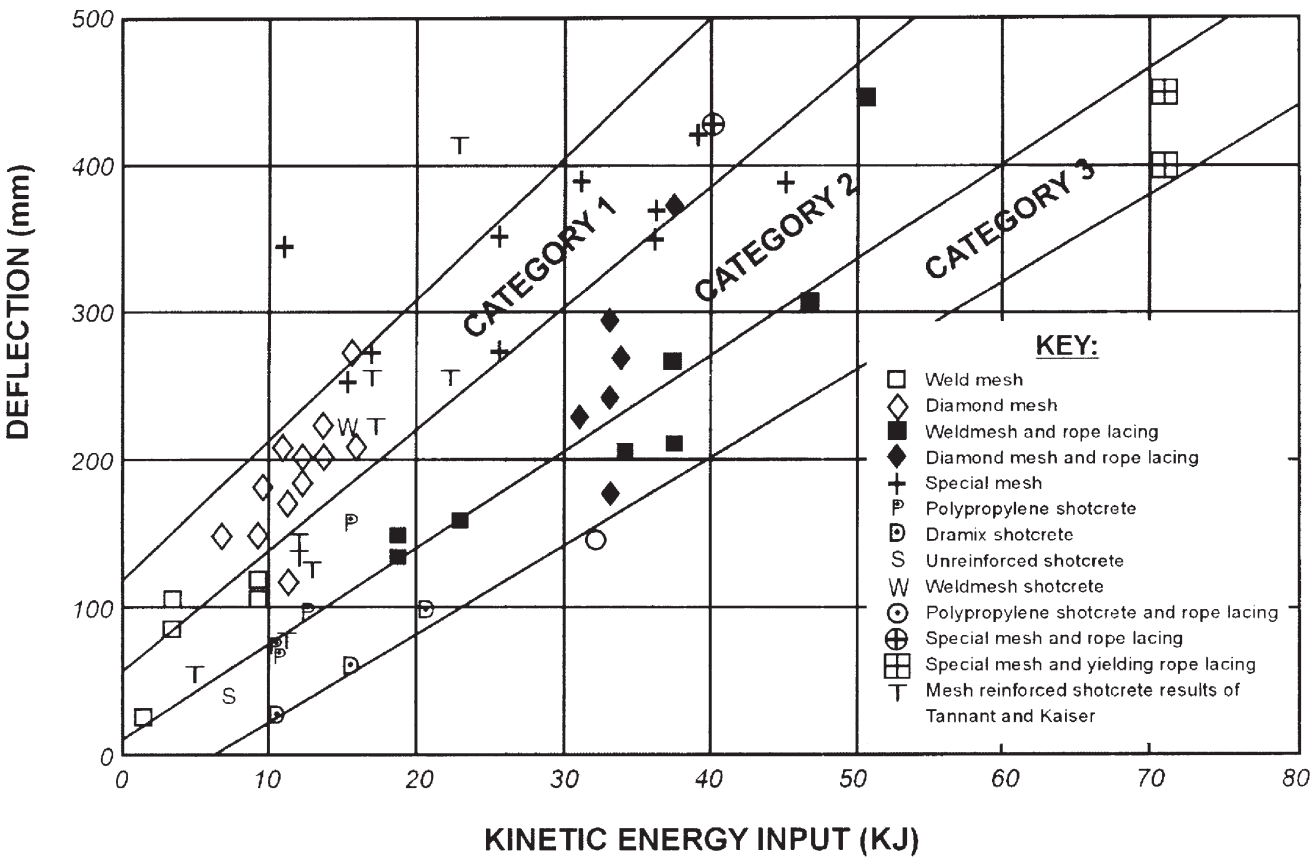

Figure 3—Results of dynamic testing of membranes

dynamic loading after it has been cracked significantly by static deformation. The testing indicated that this potential weakness is likely to be reduced or eliminated if wire rope lacing is added.

The dynamic testing showed that, with the addition of wire rope lacing to the membrane system, the capability of the system to absorb energy was considerably increased, as can be seen from Figure 3. Compared with the 'mesh only' behaviour of the weld mesh and diamond mesh, the performance characteristics of these two mesh types were reversed with the addition of lacing—the weld mesh with lacing performed better than the diamond mesh with lacing. Failure of a strand of wire of the diamond mesh generally allowed the 'rock mass' to spill through. In contrast, the weld mesh contained the rock mass even though some of the wire strands failed.

A monofilament polypropylene fibre-reinforced shotcrete panel was tested with the addition of wire rope lacing. As shown in Figure 3, it absorbed a substantial amount of energy. This occurred with cracking, but not complete failure, of the shotcrete, and the plotted point (open circle) on Figure 3 therefore does not represent the ultimate capacity of this membrane system.

Several tests were carried out with special yielding mesh, and with yielding mesh and wire rope lacing in which a yield capability was introduced. This latter support withstood, without failing, the maximum amount of energy that the testing facility could apply. This amount of energy is considered to be representative of a severe rockburst, and the results therefore demonstrate the possibility of containing this damage satisfactorily.

Subsequent to the testing programme described above, a small number of tests have been carried out using a similar but different test facility. The purposes of these tests was to evaluate the effects of different rockbolt support spacing, and different membrane thicknesses, on the performance of monofilament polypropylene fibre-reinforced shotcrete membrane components. The results of these tests showed that the performance was very sensitive to both factors, and that, for rockburst conditions, a rockbolt spacing of greater than 1.2 m, and a membrane thickness of less than a nominal 75 mm, would not be satisfactory.

Membrane capacities

The behaviour of the membrane components and membrane systems, as represented in Figure 3, can be divided broadly into three groups.

- *Category 1*: wire mesh membranes, acting as membrane components on their own. These components have varying capacity—the more rigid conventional weld mesh has the least capacity, whereas the special meshes can have more than four times this energy absorbing capacity. This category of membranes has the greatest flexibility and the result is that, in absorbing rockburst energy, considerable deformation of the tunnel walls will take place.
- *Category 2*: wire mesh and wire rope lacing membrane systems. The wire rope lacing adds considerable energy absorbing capacity to the wire mesh membrane component. It is unlikely that the individual capacity of the rope lacing has any significant effect on the deformability of the membrane system, *provided that it does not fail*. If it does fail, then the membrane system reverts to a wire mesh membrane component.
- *Category 3*: the shotcrete based membrane components and systems. Owing to their greater initial stiffnesses, the membrane systems in this category deform less than the other categories for the same energy absorption.

The results obtained by Tannant and Kaiser (1997) for dynamic loading of mesh-reinforced shotcrete are included in Figure 3. It is considered that their minor damage level results correspond with category 3 behaviour, their moderate damage level results with category 2 behaviour, and severe damage level results with category 1 behaviour. The implication of these considerations is that, under minor damage levels, the membrane behaviour is controlled by the stiff shotcrete, but under severe damage levels, the membrane is behaving as a wire mesh and the cracked shotcrete has no influence. Based on the results summarized in Figure 3, the energy absorbing capacities of the various membrane components and systems, and the corresponding characteristic deformation limits, are quantified in Table I. In this Table, based on experience and on understanding of the mechanisms of membrane component and system behaviour, estimated capacities of additional untested membrane systems have been included. These are indicated in italics. It must be noted that these membrane data are representative of a total support system with appropriately yielding rockbolts spaced at 1 m centres.

Tendon straps, which have been included in Table I, may be very effective. They have been proved to be so in large static deformation situations (Wilson, 1991), but have not yet been proven under dynamic loading conditions. They are likely to provide stiffer resistance than wire ropes in the early stages of deformation.

The results of the testing programmes described above have shown that available support elements and systems are capable of withstanding large dynamic deformations without failing. Excavations in different environments will have different requirements of membrane support. Under very high stress and significantly squeezing conditions, it is impossible, practically, to prevent significant deformation or cracking of 'brittle' membranes. Under rockbursting conditions, it is almost certain that substantial deformation and cracking of such membranes will occur. The practical requirement will be that the 'failed' membrane should continue to contain the rock, allowing the excavation to continue to perform its designed function. Stacey (2001) has indicated that the following characteristics would be desired for the ideal membrane:

- very stiff, to prevent or minimize the deformation of the rock
- large deformation capability without failure, and the ability to maintain high load capacity during this deformation
- yieldability, to absorb energy in the case of dynamic loading (and repeated dynamic loading)
- toughness, to resist mechanical damage.

It is unlikely that a single membrane with all of these characteristics will be developed. It is much more likely that

Table 1

Energy absorbing capacities and deformation limits of membrane components and membrane systems

Membrane component/ system	Input energy capacity (kJ)	Characteristic deformation limit (mm)	Comments
Unreinforced shotcrete	6	50	
Weld mesh	10	100	
Diamond mesh	15	220	
Special wire mesh	Varies, say 35	Varies, say 400	Mesh with yield capability available commercially or in which yield capability has been introduced
Weld mesh reinforced shotcrete	15	150	
Dramix fibre-reinforced shotcrete	20	100	
Monofilament polypropylene fibre-reinforced shotcrete	15	120	
Weld mesh and wire rope lacing	50	400	Wire rope lacing has some inherent yield capacity
Diamond mesh and wire rope lacing	35	300	Wire rope lacing has some inherent yield capacity
Special mesh and wire rope lacing	50	450	Wire rope lacing has some inherent yield capacity
Fibre-reinforced shotcrete and wire rope lacing	35	170	Wire rope lacing has some inherent yield capacity
Wire mesh and tendon straps	*35*	*280*	*Behaviour will depend on pattern of straps*
Fibre-reinforced shotcrete and tendon straps	*40*	*220*	*Behaviour will depend on pattern of straps*
Wire mesh and yielding tendon straps	*45*	*350*	*Behaviour will depend on pattern of straps*
Fibre-reinforced shotcrete and yielding tendon straps	*50*	*300*	*Behaviour will depend on pattern of straps*
Special mesh and yielding wire rope lacing	>70	450	
Special mesh and yielding tendon straps	*100*	*450*	*Behaviour will depend on pattern of straps*
Fibre-reinforced shotcrete and yielding tendon straps and yielding wire rope lacing	*150*	*500*	
Special mesh and yielding tendon straps and yielding wire rope lacing	*150*	*550*	

the desired solution will be achieved with the use of membrane systems, consisting of combinations of various types of membranes. As loading conditions become more severe, additional components can be added to meet the energy absorption requirements. For example, the basic support system for areas of low seismic risk could consist of yielding rockbolts, with fibre-reinforced shotcrete or wire mesh as the membrane component. As the risk of seismicity and rockburst damage increases, tendon straps could be added to form a membrane system. This system could then be enhanced for more severe conditions by adding further tendon straps or wire rope lacing. To avoid a multiplicity of components, all of the components used could be yielding components, which would maximize the energy absorption capacity. Although the component unit cost would be somewhat greater than for conventional components, the cost per kilojoule of energy absorption capacity would reduce considerably. The result could be a net decrease in the cost of support for a support system with a much greater capability.

It must be emphasised that, whatever support system is used, *all elements must be matched* in terms of capacity. There is little to be gained from the use of yielding membrane systems in combination with non-yielding rigid rebar rockbolts (shepherd's crooks). In addition, connecting elements must also be compatible. Small stiff face plates can easily pull through shotcrete, and sharp edged face plates can cause premature failure of mesh. It is recommended that retainment elements have a significant yielding capability, which will enhance their performance and life under both axial and shear deformations. The retainment elements should be stiff in their initial deformation behaviour.

One of the factors which affects support performance, which has not been dealt with above is that of corrosion of support. It has been found in practice that installed support may appear to be in excellent condition, but that, under dynamic loading conditions, it fails completely (Durrheim *et al.*, 1998). In such cases, examination often shows that the rockbolts have been corroded behind the surface containment support or where they intersect joints. This will weaken, and may totally destroy, the support. Many mine atmospheres are extremely corrosive and mine water can be significantly acidic. The rusting of steel support elements can be seen in many operations. Very rapid corrosion of steel fibres in shotcrete was observed by Venter and Gardner (1998), to the extent that the fibres no longer contributed to the integrity of the support system. Subsequent use of monofilament polypropylene fibres proved to be very successful.

The connecting elements must ensure satisfactory load transfer between containment and retainment support elements. Face plates, or other connection devices, must be of sufficient size and capacity to prevent local failure of the containment support. Tendon straps will contribute significantly to the load transfer between rockbolts and membrane support.

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Kumba Base Metals and GeoBiotics enter into technology development agreement*

Kumba Base Metals (Pty) Ltd, a strategic business unit of Kumba Resources Limited, has entered into an agreement with GeoBiotics, LLC as a technology partner to jointly further develop the GEOCOAT® heap bioleaching technology for the dissolution of zinc from sulphide concentrates. This technology offers a potential low-cost alternative for the extraction of zinc from lower grade concentrates.

The joint development agreement follows on promising results achieved during scouting tests earlier this year at Lakefield Research Africa (Pty) Limited. As the first step of the joint programme, column bioleach tests will be run on sphalerite flotation concentrates made from accumulated tailings at Kumba's Rosh Pinah mine in Namibia.

This will be followed by a large-scale demonstration run at Rosh Pinah in 2002. With the GEOCOAT® technology, coarse inert support rock is coated with a thin layer of sulphide concentrate and inoculated with bacteria after being stacked in a heap on an impermeable pad. The heap is continuously irrigated for a period of one to two months with an acidic solution containing bacteria. The solution percolating through the heap is collected in a lined pond and recycled to the heap. The dissolved zinc in the solution is recovered from a bleed stream.

The test programme will be performed at the pilot plant facility of Kumba Technology. ◆

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