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EARLY-AGE RE-ENTRY UNDER FRESH FIBRE REINFORCED SHOTCRETE

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ABSTRACT

Fibre Reinforced Shotcrete (FRS) is now used together with bolts for ground support in almost every underground metalliferous mine in Australia. Safety and economy have been the primary factors driving the widespread adoption of this system of ground support. Thickness, strength, and toughness requirements for long-term stabilization of hard rock ground are relatively well understood for the majority of ground conditions, but minimum safe re-entry times following spraying remain unclear. This issue has therefore been addressed through a series of experimental and theoretical investigations that have assessed common ground conditions in metalliferous mines and compared this to the local load capacity of a freshly sprayed FRS lining. The result is a tentative indication of minimum shotcrete strength requirements before safe re-entry is possible.

INTRODUCTION

The widespread adoption of Fibre Reinforced Shotcrete (FRS) and bolts as the primary system of ground control in underground metalliferous mines in Australia started in the early 1990s and has proceeded to the point where almost all mines now use this method. The factors driving this rapid adoption were improved economy, safety, efficacy, and adaptability to the many varied ground conditions normally encountered within a single mine. Safety was and remains an important issue in underground operations; records of incidents in Australian mines over recent years have confirmed the superior safety of FRS and bolts compared to the alternatives (1). Moreover, safety-based directives such as the 1999 Code of Practice published by the Western Australian MOSHAB (2) stipulating that all excavations over 3.5 metres in height must be stabilized unless a geotechnical assessment can proven otherwise has strongly encouraged the use of FRS and bolts.

The other factors that have encouraged use of FRS and bolts must also be considered in order to understand why this method of ground control has become so popular. The superior economy of FRS and bolts is due primarily to the increased speed of heading advance made possible through reduced in-cycle times and the reduction in re-habilitation requirements attributable to the efficacy and durability of FRS. The high efficacy of FRS and bolts is also attributable to the fact that shotcrete is applied very soon after excavation and works to stabilize the ground by locking the surface together and controlling movement more effectively than available alternatives. The adaptability of FRS is unmatched by any other system of ground control as almost any level of ground instability can be controlled using the same equipment, personnel, and daily cycle of operation. All these issues are relevant in the majority of underground excavations and therefore should always be considered when selecting a method of stabilization.

Despite the many advantages of FRS and bolts outlined above, there remain several disadvantages that have proven difficult to overcome. The primary disadvantage of this system of ground control is the lack of a quantitative understanding of how the FRS interacts with the ground. A qualitative understanding exists of how FRS works to control ground movement, but deterministic engineering models that allow engineers to design a lining for the control of movement in hard rock applications remain simplistic and probably very conservative (3). In the Australian underground mining industry, the process of ground support 'design' using FRS follows the observational approach. The toughness of the FRS is usually selected in advance from several minimum grades (Table 1) based on the expected degree of instability (4), hence the thickness of applied shotcrete is then the principal variable that is altered as conditions change. Thickness will typically range from 50 to 100 mm. The strength of the shotcrete matrix is usually selected with reference to expected lifespan and consideration of brittleness (high strength usually being equated to more brittle FRS regardless of how much fibre is added).

TABLE 1 – Toughness requirements for FRS based on expected ground conditions.

Type of Support	**Minimum Toughhess***
Low deformation	280 Joules
Moderate ground support	360 Joules
High-level ground support	450 Joules

* Energy absorption at 40 mm in ASTM C-1550 round panel test (5)

The ability of FRS to control ground movement from an age of about 3 days onward has largely been confirmed in the field provided the guidelines described above are followed. ASTM C-1550 panels and cores are used to assess FRS performance on a regular basis, and as a result shotcrete contractors in Australian mines have learnt to achieve the target performances listed in Table 1 essentially without any need for qualification trials. The fact that QC programmes for strength and toughness have been implemented in almost all underground mines has helped both contractors and miners to understand FRS much better, and has driven them to explore the boundaries of our present state of knowledge regarding this material. This is in contrast to civil tunnelling contractors who continue to labour under specifications that are usually fixed at the start of a project and allow little room for innovation.

EARLY-AGE BEHAVIOUR

Existing methods of lining design in hard rock (3, 6, 7) rely on experience accumulated in the form of charts or approximations describing the relation between ground quality, excavation span, and shotcrete thickness and/or toughness. However, none of these methods of design specifically address early-age lining capacity as they are primarily intended for later-age linings under loads anticipated over the design life of an excavated space. Several authors have assessed strength and toughness development characteristics of shotcrete at early age but have not addressed the load resistance of an in situ lining (8, 9).

Lining 'design' based on methods such as the Q-chart is generally regarded as too bothersome and conservative in a mining environment. This chart is mainly concerned with permanent support and does not reflect subtle variations in ground conditions specific to mines very well. Satisfactory ground support using FRS reinforced with macro-synthetic fibres has been found to be achievable using thinner linings than indicated by the Q-charts (6). This method is therefore used for little more than budgeting. However, the concept of using charts and simple tables to guide the selection of FRS lining thickness, strength, and toughness requirements in various ground conditions, particularly for early age re-entry requirements, has merit. Simple graphical or tabular guidelines for the determination of safe re-entry times after spraying have therefore been the goal of the present research.

MODEL DEVELOPMENT

The first stage of the investigation examined the modes of failure that early-age FRS suffers in situ. Loading was assumed to comprise loose rock, primarily single blocks, acting under gravity, as areas of rubble have been assumed to be removed by scaling. A series of experiments were undertaken in the laboratory involving a wall to which so-called 'pull-out disks' were attached. This wall was sprayed with fresh FRS and the previously attached disks were withdrawn through the fresh FRS using an hydraulic actuator. Full details of the equipment and procedures used are described by Bernard (10). This process resulted in punching shear failure of the FRS over the first few hours after spraying, but this changed after several hours to a flexural mode of failure involving delamination of the lining (Figure 1). This confirmed the initial suspicion that shearing would play a central role in estimation of early-age lining capacity. The transition to a flexural mode was also anticipated as this type of failure has been observed in mature linings in the field.

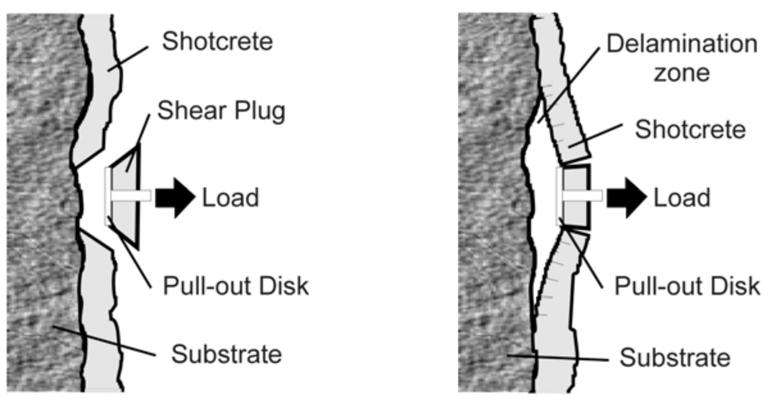


Figure 1. Failure modes involving punching shear or delamination and flexure.

Following confirmation of the early-age failure modes for a FRS lining, two further series of laboratory tests were undertaken to extend the range of data available concerning load resistance at early ages. These were undertaken on successively larger planar linings. Punching tests (Figure 2) and both direct and indirect UCS tests were performed using the methods described by Bernard & Geltinger (11) to provide complimentary performance data. These tests indicated that the shear failures observed in situ were essentially indistinguishable from direct punching tests conducted on constrained panel specimens in a test machine. Moreover, the point at which the mode of failure changed to flexural appeared to be determined by the adhesive strength of the lining to the underlying substrate.

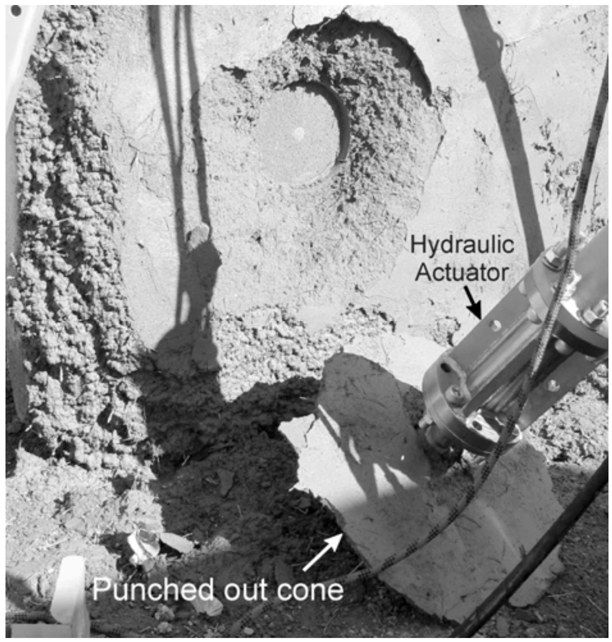


Figure 2. Punched out cone of shotcrete following laboratory test.

A second important observation gained from the laboratory tests was that the punching mode of failure exhibited considerable post-crack strain-softening, that is, the fall in load resistance after cracking of the concrete matrix was abrupt. This appeared true for both steel and macro-synthetic FRS. In contrast, the flexural mode was much more ductile and total energy absorbed through this mode of failure far exceeded that absorbed through shearing. The punching mode of failure also offered little opportunity for redundant load transfer following cracking of the concrete matrix and thus a failure could be considered ‘catastrophic’. Both these points underscored the importance of avoiding a shear mode of failure.

FIELD TRIALS

The laboratory trials established the procedures required to acquire data on lining performance but could not generate information on the capacity of real in situ linings. The equipment developed in the laboratory was therefore transported to several mines around Australia and used to assess the point load capacity of FRS linings as sprayed. Trials were conducted using several different mix designs containing either Dramix RC65/35 steel fibres or Barchip Shogun macro-synthetic fibres (Figure 3). The typical in situ 28 day compressive strength of concrete used was 40 MPa, and lining thickness ranged from 50-100 mm.

Figure 3. Spraying shotcrete over pull-out disks during in-field tests.

Almost all the pull-out tests conducted in the field resulted in a punching shear failure of the lining accompanied by generation of a cone of sheared concrete around the pulled-out disk. Delamination and flexural failure of the lining occurred in only a few tests and was associated with poor bond between the lining and a slicken-faced serpentine substrate. All of the peak load capacities and associated direct and indirect compressive strengths (measured concurrent to the shear tests) have been converted into shear and equivalent UCS data (Figure 4). It was notable that shear resistance was independent of the type of fibre used in the FRS. These results also indicated a highly non-linear relation between shear and compressive strengths that deviated substantially from the general relation accepted for later-age 'mature' concrete. It is un-conservative to use the standard relation between characteristic compressive strength f_c' and shear strength ν (both in MPa), represented by the expression

$$\nu = 0.34\sqrt{f'_c} \tag{1}$$

or the tensile strength of concrete, f_t, given by

$$f_t = 0.42\sqrt{f'_c} \tag{2}$$

when estimating the early-age shear strength of FRS. Instead, the following relation was fitted to the full range of data obtained:

$$\nu = 0.28 f_c^{\ 0.6} - 0.11 \tag{3}$$

in which f_c is the measured average compressive strength of the shotcrete. The local punching shear resistance of the lining can then be estimated as

$$V = \nu pt \tag{4}$$

where V is the shear resistance, t is the thickness, and p is the critical perimeter around the punching zone. This expression is the same as that used for punching through a suspended concrete floor slab (eg. 12).

The shear resistance of a FRS lining can be found using Equation (4) if the shear strength ν can be determined and the likely size of a punched out zone estimated. If the shear resistance exceeds the load action P on the lining by a suitable margin, then it can be considered safe to re-enter provided the possibility of large-scale ground instability can be excluded. To determine the load action on a lining, the size of block or rock wedge that may pose a danger of falling out at early ages and its associated punching perimeter must be estimated through a geotechnical assessment of conditions at hand. The shear strength of FRS is difficult to determine in situ, but the data in Figure 4 can be used to find the shear strength indirectly based on measured estimates of compressive strength which can be determined quite readily (11). Assuming the perimeter length, lining thickness, and shear strength can be estimated then it is a simple task to calculate shear resistance. However, it must be noted that failure to develop adequate bond strength to the substrate can cause the mode of failure to prematurely change to flexure as the concrete hardens, hence it is necessary to check bond strength and confirm that adequate bond is possible. Methods of achieving this were described by Bernard (10).

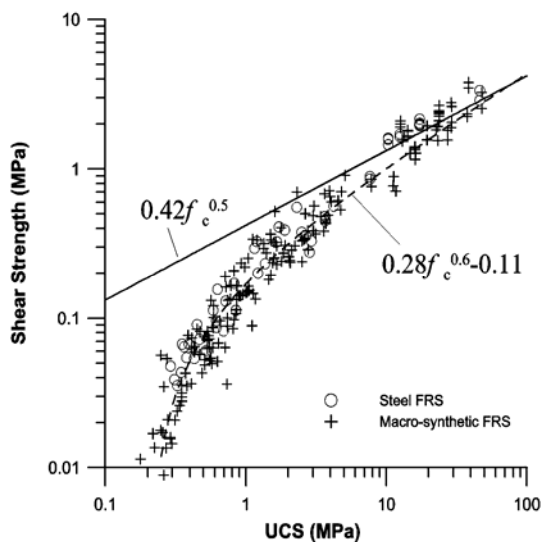


Figure 4. Relation between compressive and shear strengths at early age.

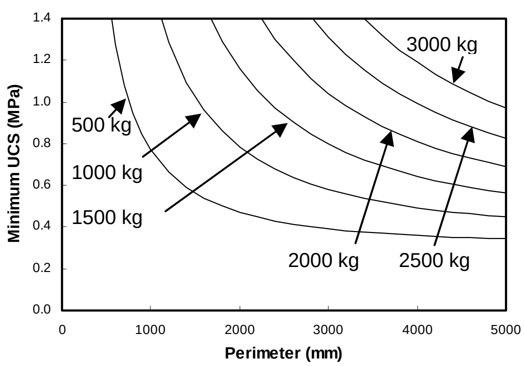
To illustrate the shear capacity of a typical FRS lining, the idealized case of an approximately circular punching zone of critical perimeter radius r can be examined to estimate the compressive strength required to stabilize individual loose rocks. The load P acting on a punching zone comprises the self weight of the shotcrete lining and the surcharge P' associated with the loose rock. This can expressed

$$P = \rho \pi r^2 t + P' \qquad (5)$$

in which ρ is the density of the concrete (typically 2350 kg/m^3). The minimum compressive strength $f_{c.min}$ required to resist the lining self-weight and surcharge is then found by re-arranging Equations 2 and 3 to obtain

$$f_{c.\min} = \left(\frac{\phi P}{0.28pt} + 0.3928 \right)^{5/3} \qquad (5)$$

in which ϕ is a factor of safety (which can be taken as equal to 1.3 for short term support). Anecdotal evidence suggests that loose scats average between 500 kg and 2000 kg in mass (1). One approach to the estimation of the minimum strength required before safe re-entry is possible is to estimate the mass and perimeter of the loose rock independently and select an appropriate safety factor to use in Equation (5). Once $f_{c.min}$ has been determined, checks must be undertaken in the field to assess how long it takes for the shotcrete to reach the required minimum compressive strength. Since temperature, cement chemistry, and set accelerator dosage rate all have an effect on early hydration, checks must be carried out in situ on a regular basis. Example results for $f_{c.min}$ are shown for a 50 mm thick lining in Figure 5, but it should be noted that some combinations of mass and perimeter shown here are unlikely.



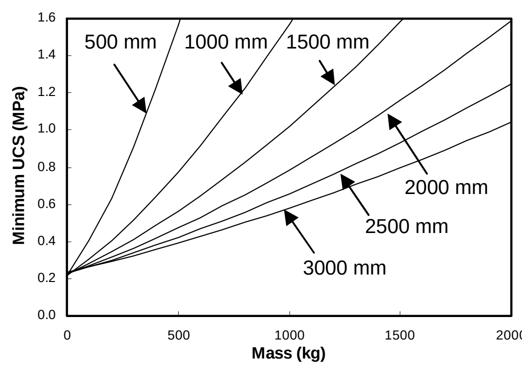


Figure 5. Minimum compressive strength required to support a loosened irregular rock mass for a lining thickness of 50 mm and ϕ = 1.3.

Since perimeter is in the denominator, it is most conservative to consider a fall-out with a circular face rather than the commonly assumed triangular shape since a circle has a higher ratio of area/perimeter. Hence the minimum compressive strength required to resist a roughly hemispherical rock of between 500 kg and 2000 kg mass has been calculated and plotted in Figure 6 for linings of between 50 and 100 mm thickness (rock density taken to be 2600 kg/m^3 and ϕ = 1.3). As lining thickness is increased, a lower minimum strength is required before safe re-entry is possible. These examples indicate that the commonly used benchmark of a minimum 1 MPa compressive strength before safe re-entry is possible appears quite conservative even for a 50 mm thick lining. Appropriate margins to place on minimum strength requirements remain to be confirmed.

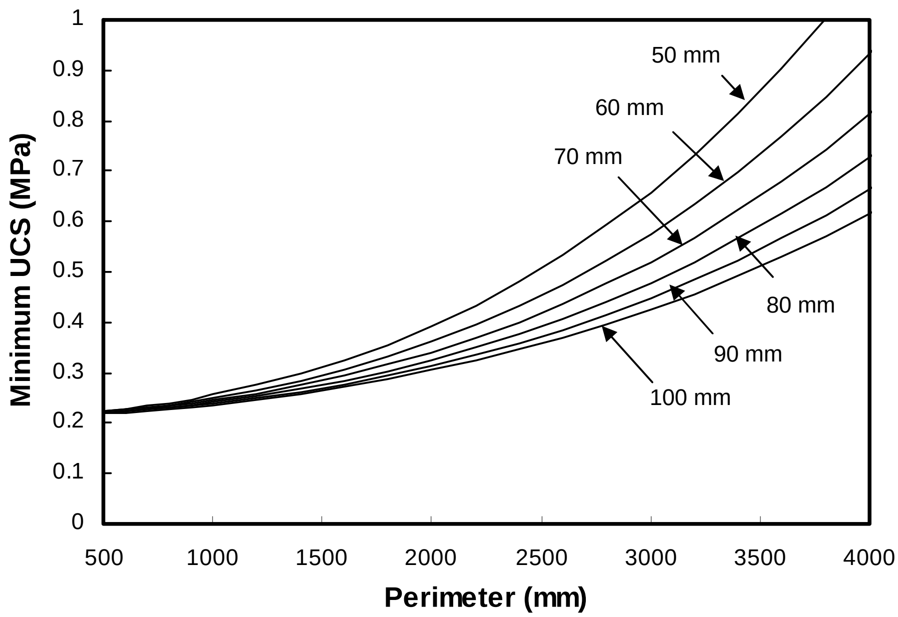


Figure 6. Minimum compressive strength required to support a loosened hemispherical rock mass for lining thicknesses of 50 to 100 mm, $\phi = 1.3$.

CONCLUSION

The present investigation has revealed a number of important findings regarding the load capacity of early-age shotcrete linings. The first is that early-age shotcrete primarily experiences shear failure in response to load actions associated with individual loose rocks or wedges impinging on the lining, but this transitions to delamination from the substrate and flexural failure as the shotcrete strengthens. Secondly, there is a well-defined relation between shear and compressive strengths over the first few days of strength gain that is markedly different from that derived for mature concrete despite the fact that the modes of failure are very similar. The shear strength of early-age FRS is substantially lower than one would estimate based on common models of shear strength in mature concrete, thus it is unconservative to extrapolate the performance of mature FRS to early ages. In addition, early-age punching shear strength appears to be independent of the type of fibre used to reinforce the shotcrete.

In estimating the time to safe re-entry, the compressive strength of the in-place concrete can be used to estimate the shear strength and this, in turn, can then be used to calculate the shear resistance of the lining. If the shear resistance exceeds the loads associated with loose scats by a suitable margin, then safe re-entry may be possible. However, it is necessary to confirm that bond strength development to the substrate is adequate otherwise a flexural load of failure may occur in preference to punching shear. If this occurs, an alternative means of estimating load resistance must be used.

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NOTATION

The following symbols have been used in this paper.

f_c	mean compressive strength of concrete
$f_{c.min}$	minimum compressive strength of concrete
f'_c	characteristic compressive strength of concrete
p	critical perimeter
P	ground load acting on lining
P'	surcharge on lining due to self-weight
r	radius of punching zone
t	lining thickness
V	lining shear capacity
ρ	density
ν	shear strength
ϕ	capacity reduction factor

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