INVESTIGATION INTO THE EXTENT AND MECHANISMS OF GLOVING AND UN-MIXED RESIN IN FULLY ENCAPSULATED ROOF BOLTS

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ABSTRACT: Effective strata control, utilising fully encapsulated roof bolts is dependent on the installed quality of the reinforcement elements. One mechanism by which roof bolts may become less than fully efficient is by glove fingering (gloving) and un-mixing of the resin. Following a routine installed bolt quality audit and some small roof failures containing gloved bolts, a work programme was initiated to determine the extent of the gloving and un-mixing problem and to develop an understanding of mechanisms involved. Results have shown that gloving and un-mixing is a systematic and widespread phenomena, occurring across the range of resin and/or bolt manufacturers, and in a variety of roof types. Gloving was found in bolts installed using either hand held pneumatic or continuous miner mounted hydraulic bolting rigs, under run of mine (ROM) conditions by operators, and under controlled manufactures "best practice" conditions.

The mechanisms involved have been confirmed as being the development of a pressure front as the bolt encounters the resin cartridge and is spun up the hole, which in turn, leads to over-pressurisation and radial expansion of the resin cartridge. The result is an increase in the diameter of the plastic cartridge. Allowing the bolt to be spun up inside the cartridge without making sufficient contact to shred the cartridge or the hardener envelope, typically resulting in a portion of the cartridge enveloping the bolt and unmixed resin mastic and catalyst.

Once the mechanisms involved and extent of the problem became clear, further research was undertaken to assess alternative bolt profiles and modifications in an effort to minimise and/or eliminate the gloving and un-mixing phenomenon. Research has been undertaken using recovered bolts from various mine sites, as well as test bench trials and the quantification of the loading characteristics of gloved bolts using strain gauge roof bolts.

To understand the impacts of gloved and un-mixed bolts on roof control, failure pathways and reinforcement requirements a FLAC 2D numerical simulation was undertaken, with the results being incorporated into the strata management plan for a particular operation. Laboratory data has been collected and analysed to assess magnitudes of resin pressure as the bolt encounters the cartridge[1] and the effects of gloving and un-mixing on the load transfer characteristics of the resin bolt system.

INTRODUCTION

Gloving, in this context, refers to the plastic cartridge of a resin capsule partially, or completely, encasing a length of bolt, typically with a combination of mixed and unmixed resin filler and catalyst remaining within the cartridge. The gloved and unmixed portion reduces the effective anchor length and adversely affects the ability to reinforce the roof strata. Figures 1, 2a and 2b illustrate typical examples of gloved roof bolts and un-mixed resin/catalyst.

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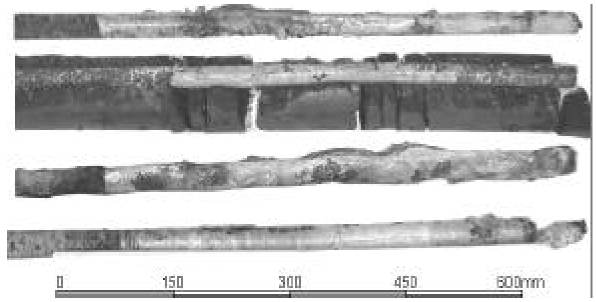


Fig 1 - Typical appearance of gloved and un-mixed bolts.

Gloving has been recognised in fully encapsulated roof bolts for many years (Pettibone, 1987) and has traditionally been attributed to poor installation methods, issues relating to drilling/installation equipment, poor handling and/or storage of consumables or geological issues resulting in abnormal ground conditions. Very little quantitative data is available in the public domain, although recent work by Campoli *et.al*. (2002) and Campoli, Mills, and Adams (2003), Fiscor (2002), Campbell and Mould (2003), and Pasters (2003), along with hazard alerts from the Queensland Mines Inspectorate (Qld Govt 2002) have brought some focus to the problem. Fiscor (2002) refers to gloving being identified as the cause of roof falls in American operations; in one of the few published references directly linking gloved bolts and falls of ground.

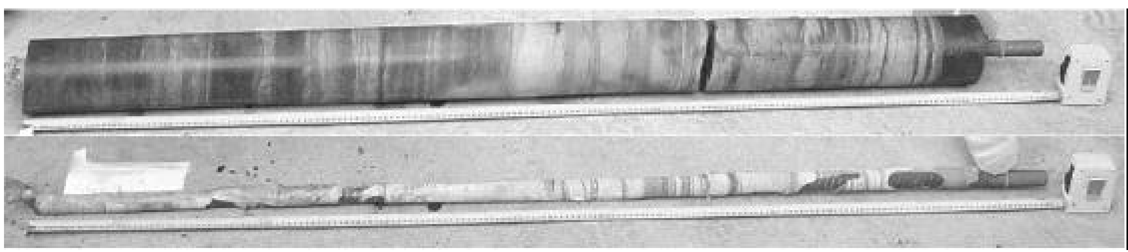


Fig 2(a) - Upper photo shows intact core in stone roof.

Lower photo illustrates how once the core is removed the gloving and un-mixing is revealed, in this case 550mm was found to be gloved and un-mixed.
Note: Bolts are photographed with the top of the bolt on the left hand side and the nut and plate on the right hand side.

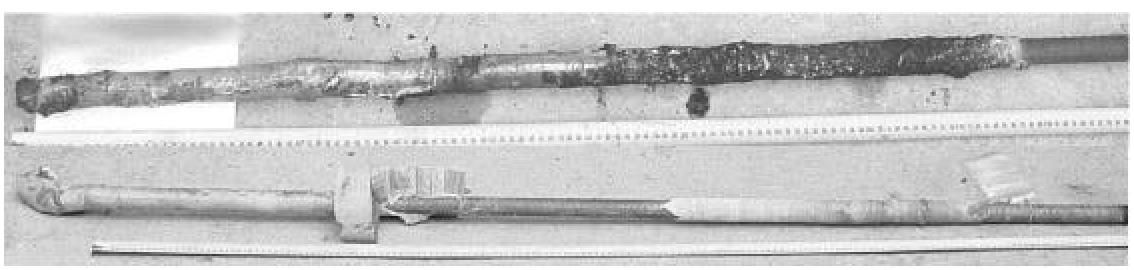


Fig 2(b) - Typical examples of gloved and un-mixed bolts.

Note: Bolts are photographed with the top of the bolt on the left hand side.

LOAD GENERATION AND TRANSFER IN RESIN GROUTED ROOF BOLTS

The performance of any reinforcement design is limited by the efficiency of load transfer of the reinforcing members. Load transfer is the mechanism by which force is generated and sustained in the roof bolt as a consequence of strata deformation (Fabjanczyk and Tarrant 1992).

In a fully grouted roof bolt the load transfer mechanism is dependant on the shear stress sustained on the bolt-resin and resin-rock interfaces. The peak shear stress capability of the interfaces and the rate of shear stress generation, determines the response of the bolts to the strata behaviour. This concept is illustrated in Figure 3.

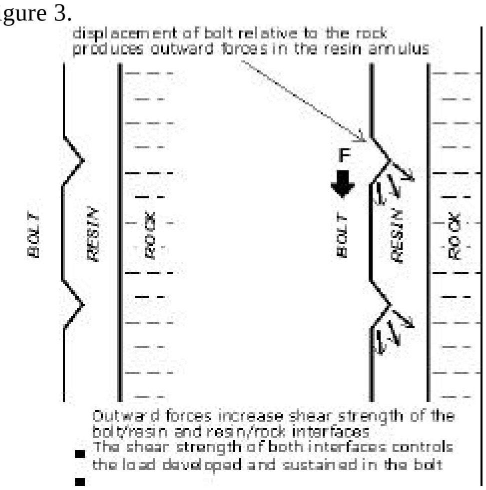


Fig 3 - Mechanism of load transfer (after Fabjanczyk and Tarrant 1992).

OVERVIEW OF INVESTIGATION PROGRAM

The work program reported here was undertaken over the past 2 years as part of an audit of the installed quality and effectiveness of roof bolts in various coal mining operations. The initial investigation program concentrated on defining the extent of the problem and developing an understanding of the mechanisms involved, this was then followed by a series of trials aimed at finding an acceptable solution. The latter involved trials of alternative bolt/resin suppliers and modifications made to bolts based on the understanding of the mechanisms involved.

The over coring method allowed the recovery of bolts installed ROM by operators at the face and in the back-bye districts of the mines, as well as to audit bolt installations under controlled manufacturers "best practice" conditions using either pneumatic (gopher/wombat) or hydraulic (miner mounted) drilling rigs. At each operation standard drilling consumables were used, and a strict measurement and recording protocol was defined to ensure the same parameters were recorded so that all results were comparable. Over coring was undertaken using specialist techniques and equipment, drill bits and barrels developed by SCT Operations, using either a Proram or Ramtrak drill rig. Stone roofs were typically drilled with a diamond bit and coal roofs with a tungsten-tipped bit. In addition to the over coring program, bolts of various type, age and manufacturer have been collected from falls of ground and goaf edges for comparison and to assist in gauging the extent and history of the issue. Further quantitative data has also been gathered using strain gauge bolts, installed to measure the loading characteristics of the gloved bolts.

EXTENT OF THE GLOVING PROBLEM

In excess of 80, 1800mm long roof bolts of four different types/manufacturers were over cored and recovered to date. The bolts have been recovered from five separate operations, in different geological and geotechnical settings, with the immediate bolted section comprising a range of lithologies from thick coals to more typical shale/mudstones and sandstone/laminites. The over cored bolts investigated had been installed for time spans, ranging from hours to up to 18 months.

Bolts and resins used in this program are from various manufacturers and suppliers in Australasia. The resin cartridges used were all two-part polyester (fast/slow setting times), 900-1000mm long and nominally 24mm in diameter. The bolts used were all flat topped, with a core thickness of 22mm and 1 to 2mm ridge profiles, with ridge spacing depending on manufacturer and bolt type.

The investigation program was undertaken in two phases, the first being the recovery of ROM installed bolts from throughout the five mine sites to assess if gloving was routinely occurring. The second phase was to undertake controlled "best practice" installations (often with a manufacturers representative present) to determine if an acceptable quality bolt (nil gloving and un-mixing) was achievable. Both data sets are presented here. The results of the investigation work are summarised in Figure 4 in terms of bolt and resin type/manufacturer, roof lithology and installation type, ie controlled or ROM.

As illustrated in Figure 4, regardless of bolt type, roof lithology or if the bolts were installed by miners ROM or under best practice controlled conditions, an average of 500mm of bolt length is typically affected by gloving, with 200mm typically gloved and mixed and 300mm typically gloved and un-mixed. Although it must be noted that there is a wide range in values in the data set, (from 30mm to 790mm), with the majority of the data set (70%) having in excess of 400mm un-mixed length.

The over coring program graphically illustrated that gloved and un-mixed bolts were common at all sites investigated regardless of roof lithology and occurs across the range of bolt and/or resin manufacturers. The results also indicate that there is little difference in ROM bolts and those installed under "best practice" controlled conditions. In fact, it is apparent that an acceptable quality bolt is typically not achievable using the current flat-topped bolt and cartridge systems on the market. As such it can be concluded that gloving and un-mixing is not the result of poor installation methods, issues relating to drilling/installation equipment, poor handling and/or storage of consumables or geological issues resulting in abnormal ground conditions.

In addition to the over cored bolts several areas of falls in back-bye regions and goaf edges of mines were inspected in an attempt to find bolts of differing ages and resin cartridge configuration to determine the time span over which gloving has been a problem. To date bolts ranging in age from hours to in-excess of 12 years have been recovered, all of which show a similar degree of gloving and/or un-mixing, indicating that it is an issue that has been prevalent in the industry for a considerable time.

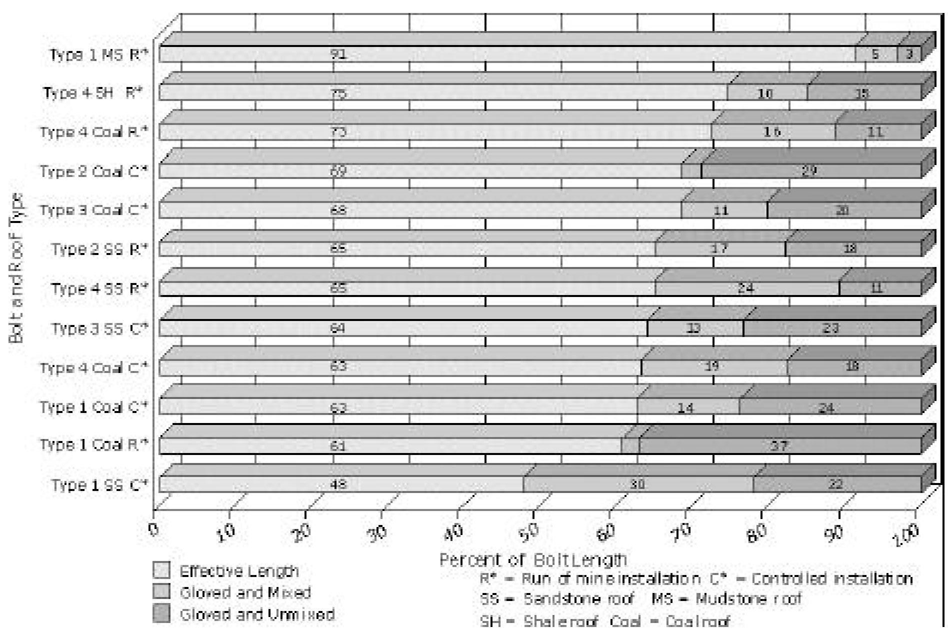


Fig 4 - Gloving investigation summary of results for standard bolts.

GLOVING MECHANISM

Determining the mechanism for gloving and the resultant un-mixing has been the focus of much of the preliminary investigation work. From observations of bolt installation, over cored bolts and from test bench trials and measurements, an understanding of the mechanisms has been developed and confirmed. This is discussed below.

A pressure front develops when the standard flat-topped bolt encounters the resin cartridge as it is spun and pushed up the hole. The bolt acts essentially as a piston hydraulically pressurising the resin and cartridge, which shortens and in turn undergoes radial expansion until it is confined by the sides and the back of the drill hole.

The result being an increase in the cartridge diameter from 24mm to the diameter of the drill hole, nominally 27 to 29 mm. In conjunction with the expansion against the drill hole wall, the catalyst envelope/tube also becomes flattened against the side of the drill hole.

The increased cartridge diameter allows the bolt (nominally 22mm core and 24mm rib diameter) to be spun up inside the cartridge without making sufficient contact to shred the cartridge or the flattened hardener tube. Culminating in a portion of bolt encased in intact cartridge and typically a combination of mixed and unmixed resin mastic and catalyst.

To confirm the causes of gloving, test bench simulations were undertaken in clear 28.5mm internal diameter polycarbonate tubing so that direct observation of the gloving mechanics could be made as the bolt was installed. Visual conformation of the pressure front development and of the bolt entering the cartridge (gloving) was possible.

The observations showed that the pressurisation of the cartridge reaches sufficient levels to expand the cartridge against the wall of the tube at 600 - 700mm from the end of the 1800mm tube, and it is at this point the bolt enters the resin cartridge. Once the bolt was spun up inside the expanded cartridge no further shredding of the cartridge took place, resulting in a 600-700mm gloved and un-mixed length of bolt, replicating the field observations, and confirming the mechanisms involved.

UP-HOLE DYNAMIC PRESSURE

Up hole dynamic resin pressures have previously been measured (Mills, 1999) using a pressure transducer through a hole in the top cap of a 27-27.5mm polycarbonate tube under test bench conditions designed to closely simulate field installation of roof bolts. The dynamic pressure was shown to rise to its peak of around 4MPa very rapidly as the bolt was spun up the hole with the maximum pressure developed after 4 seconds, which equates to the bolt being approximately 1100 to 1200mm up the hole. Figure 5 illustrates the results generated.

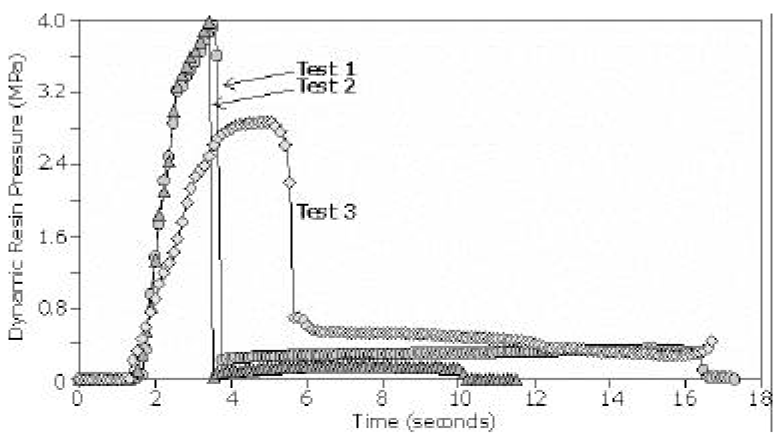


Fig 5 - Measured up-hole dynamic resin pressure as bolts

It is worth noting that the peak values recorded may not be the actual maximum pressure due to problems maintaining the transducer fittings, as the pressures were such that the end-cap detached and in some cases the polycarbonate tube split.

Up-hole resin pressures in excess of 4MPa are considered to be sufficient in magnitude to induce hydraulic-fracturing of strata and joints in situations where minor horizontal stress is of the same order of magnitude. Hydraulic fracturing causing the initiation or opening of joints or cleat, results in the injection of resin into the strata and can lead to significant loss of encapsulation length. Indeed resin injection into strata was commonly observed in over-cored bolts along with considerable loss of encapsulation. Typically resin could be observed in the drill core to radiate out from the bolt-hole to in excess of the diameter of the recovered core (Ø100mm) and be up to 2-3mm thick. Examples of resin injection as a result of hydro fracturing are illustrated in Figures 6a, 6b and 6c. The volume of resin loss is sufficient to significantly reduce the encapsulation length, which was found in extreme cases to be less than the length of the installed resin cartridge.

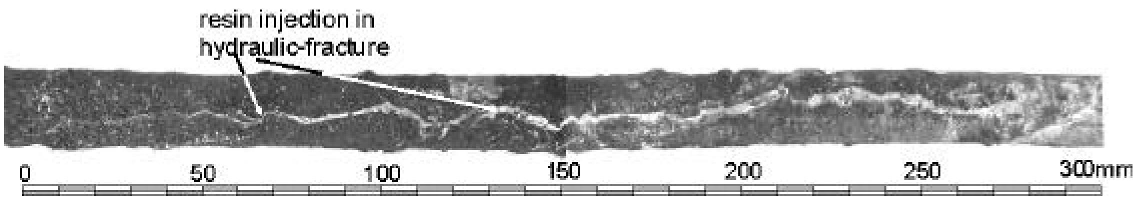


Fig 6(a) Example of resin injection into an induced fracture.

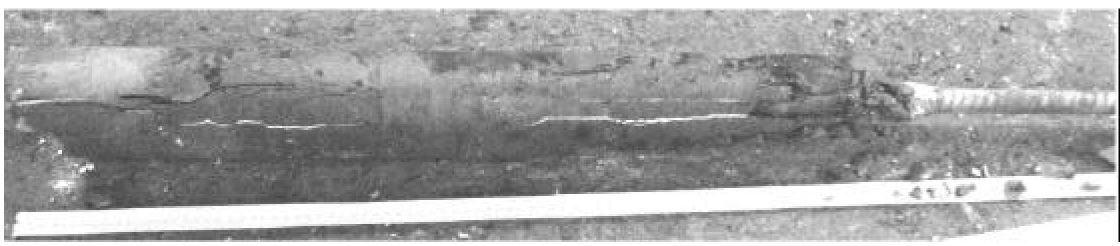


Fig 6(b) - Resin injection into an induced fracture in an all coal roof.

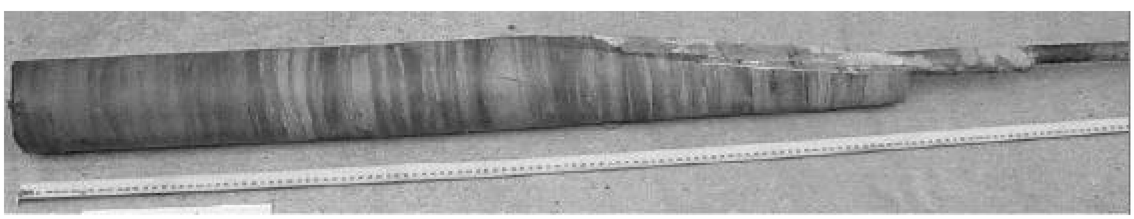


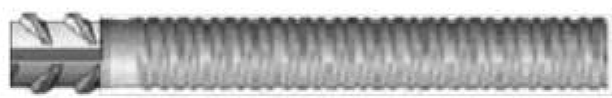
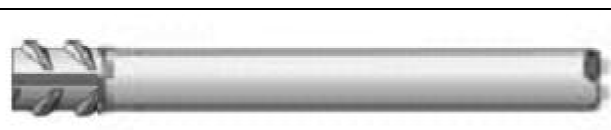
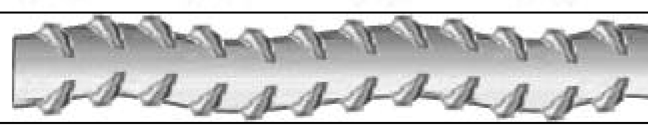
Fig 6(c) - Resin injection along a joint in interbedded sandstone and mudstone roof.

TRIALS OF ALTERNATIVE BOLT PRO FILES AND TIP CONFIGURATIONS

Following the recognition of the extent of the problem and the understanding of the mechanisms involved, a considerable effort was made to develop a solution, using bolt tip modifications suggested by a range of sources (operators to consultants) and alternative profiles available on the market as recommended by various bolt manufactures.

Trials were undertaken across several of the mine sites to cover the same range of geotechnical conditions. In total a trial of 9 alternative profiles and tip modifications was undertaken, with details of bolts given below in Table 1. Some 95 bolts were recovered across the spectrum of modifications and mine sites. At all trial sites standard bolts were also installed and recovered as a control to ensure that the modifications could be directly compared to standard profile bolt types.

Table 1 - Details of Modified and Trial Bolt Profiles

Modification Type / Bolt Name	Description	Schematic Diagram
chamfered	Curved wedge of bolt removed from tip	
Welded	Bar of weld built up on opposite sides of bolt	
Horn	Two 'horns' built-up onto tip and sides of bolt	
Paddle	Tip flattened to form a paddle shape	
Peeled and Threaded	Ribs peeled off 160mm of bolt, and thread rolled on	
Peeled	Ribs peeled off 160mm of bolt	
Spiralled Wire	Spring wire attached to tip and wound along bolt	
200mm wiggled	Standard bolt with wiggle profile over upper 200mm of bolt	
Off-centre	Nut made off centre relative to the bolts long axis	

The results of the trial are summarised in Figure 7, which illustrates the average proportions of bolt length that were affected by gloving and un-mixing. Initial trials (June 2002) were carried out using the chamfered, horn, welded, paddle, peeled and peeled and threaded bolts. The spiralled wire, 200mm wiggled and off-centre type of profiles were only recently trialed (May 2003).

It can be clearly seen that of the modifications tested only the chamfered, wiggled and off-centre bolts offered any significant improvement, with each achieving in-excess of 90% effective bolt length. The remaining modifications showed only minor or very inconsistent improvements in both mixing and shredding of the cartridge. The result of the modification and alternative bolt profile trial indicates that significant improvements in resin mixing and shredding of the cartridge was consistently achieved using the chamfered, wiggled and off-centre types of bolts.

The results of the initial trials of the chamfered bolt were considered so successful at the time that this modification was adopted as the standard bolt profile in a large scale trial at one of the mine sites involved. More recently the 200mm wiggled profile bolt has been introduced as the standard roof bolt at that mine.

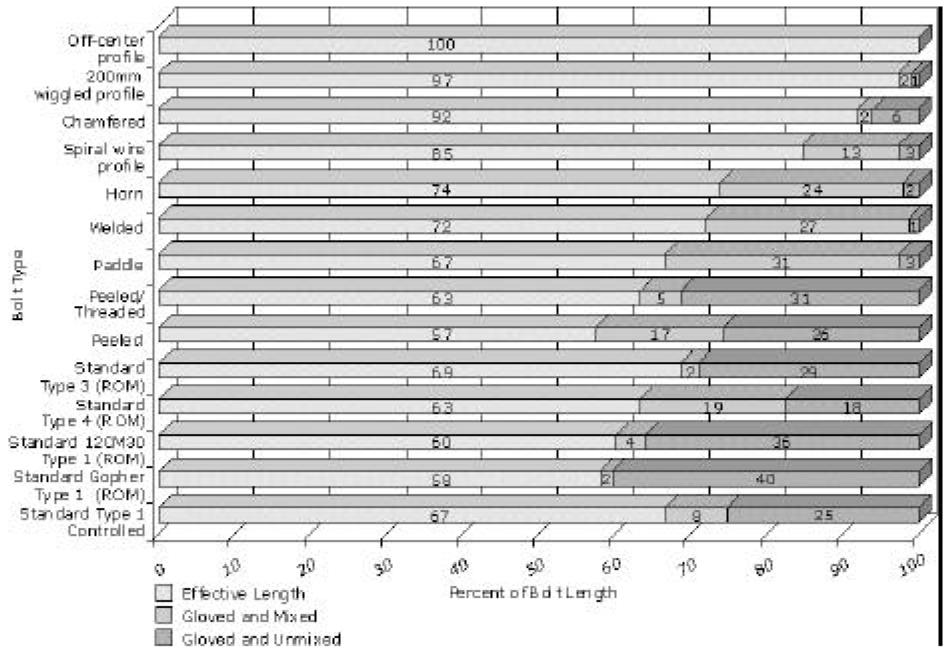


Fig 7 - Summary graph of average modified bolt performance.

LOADING CHARACTERISTICS OF GLOVED AND UN-MIXED RESIN

The use of instrumented roof bolts to quantify the loading characteristics of a gloved roof bolt was investigated. The results presented in Figure 8 show that the bolt (which was installed ROM by operators) was indeed gloved over the upper 400mm, as indicated by nil load transfer over that portion of the bolt length

The resultant loading profile illustrated that the bolt was able to generate significant load over the shorter length and was not approaching yield.

The use of a modified instrumented bolt as part of a ROM installed quality audit is currently being explored, as the results shown in Figure 8 illustrate that they are able to identify the extent of gloving and may be a cost effective, non-destructive alternative to over coring as a means of assessing if gloving and un-mixing is occurring in any operation.

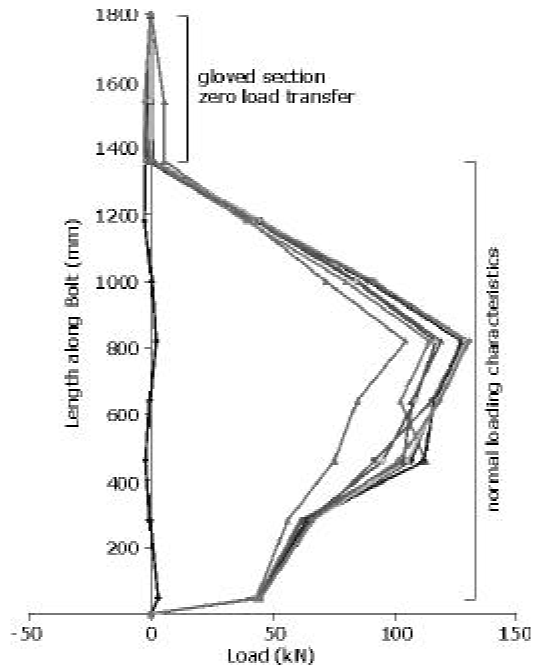


Fig 8 - Results of an instrumented roof bolt showing nil load transfer over gloved section.

LABORATORY PULL TESTS TO QUANTIFY THE EFFECTS OF GLOVED AND MIXED RESIN

Gloving of the bolt by the cartridge, where the resin has hardened, may adversely affect the load transfer characteristics of the bolt system by reducing the system stiffness and by providing a low friction interface reducing the magnitude of the shear stress sustainable on the bolt/resin/rock interfaces.

Short encapsulation pull tests undertaken by the United States Bureau of Mines (USBM) on gloved bolts indicated that there was no detrimental affect to the load transfer characteristics caused by mixed and hardened resin encased in the plastic resin cartridge (Pettibone, 1987). Pettibone also reported that the cartridge did not provide a surface, which would promote shear under heavy loads. The detrimental effect of gloving on short encapsulation pull tests has been discussed (Mazzoni et.al., 1996; Mark et.al., 2002).

In order to attempt to quantify the impact of gloved and mixed resin on load transfer characteristics laboratory short encapsulation pull tests (180mm) were undertaken at the University of New South Wales School of Mining using the rock bolt testing facility. Inspection and analysis of short encapsulation pull test specimens was undertaken to quantify relative proportions of gloving/unmixing and gloving/mixing. All of the test specimens exhibited some degree of gloving and un-mixing, with only 4 specimens having significant (greater than 10mm) gloving and mixing. The peak shear strengths (normalised for the actual effective resin length) were then correlated to the proportions of gloving and mixing.

The results, while not considered to be statistically representative, do indicate that the load transfer of the bolt/resin system is not significantly reduced by a gloved and mixed section of bolt, with the data scatter being within the same range of results as that of the shredded and mixed bolts.

IMPLICATIONS FOR DESIGN

The wide spread nature of the gloving problem led to the realisation that the current roof support design assumptions were compromised along with the subsequent deformation trigger levels which form a major component of most strata management plans. The decision was made to case study a mine site where a calibrated numerical (FLAC 2D) model existed and a significant amount of field observation and roof deformation monitoring data was available to assess the impacts of the reduction in effective bolt length on the strata behaviour and stability of an opening.

The FLAC model was used to simulate two different support configurations using 1800 mm bolts. In the first case it was assumed that the bolts were fully encapsulated, and 100% effective. In the second the top 600mm of the bolt was gloved and encased in un-mixed resin, effectively making the bolts 1200mm long. The length of gloving and un-mixing was consistent with the recovered bolts for that operation.

All other parameters were kept constant in the models, these being the excavation size/geometry, the geology and geotechnical setting (depth of 200m, 4m coal roof) and load transfer characteristics of the effective bolt lengths.

A range of horizontal stress magnitudes (5 – 10MPa total stress, based on previous 3D over core stress measurements) were simulated to compare against the performance of 1.2m and 1.8m long bolts in the same environment. In this way the general stability curve (with respect to overstressing) for each bolt length is established.

Figure 9 details stability curves for the 1.2m and 1.8m long bolts showing total roof displacement versus horizontal stress. The modelling indicates that the gloved and un-mixed 1200mm bolts become overloaded earlier (at a lower stress level) than the 1800mm long, 100% effective bolts.

In the case of the 1200mm bolts, once over stressing and shear initiates in the roof, the failure path is rapid, with softening above the bolts and mobilisation of the contact at the top of the seam at lower displacement levels. For example softening above the bolts occurs at a displacement of 10mm for 1200mm bolts, compared with 15mm for 1800mm long bolts.

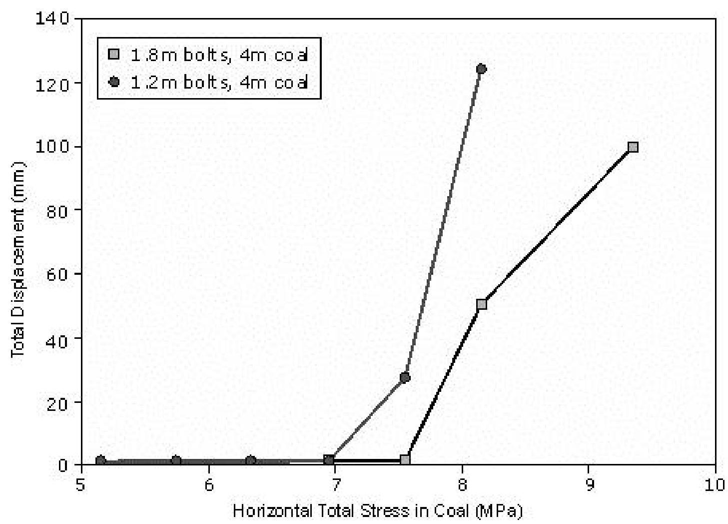


Fig 9 - Roof stability pathway with respect to applied horizontal stress.

Figures 10a and 10b detail FLAC model outputs of strata softening occurring for the same horizontal stress level. The magnitude of the horizontal stress modelled is 7.5MPa (total stress) in both situations, which was considered representative of the mining conditions at the time, based on observations of guttering and roof deformation levels. It can be seen that the longer bolts are better able to confine the immediate roof and act as a pattern to cope with a wider range of conditions while the gloved bolts act as isolated reinforcing members.

The findings of the modelling, and revised trigger levels have since been incorporated into an updated Strata Management Plan for the affected areas. Simultaneously a review and re-analysis of the existing roof deformation monitoring data (from wire extensometers) was undertaken to assess which areas of the mine were potentially requiring remedial secondary support at the revised lower magnitudes of deformation.

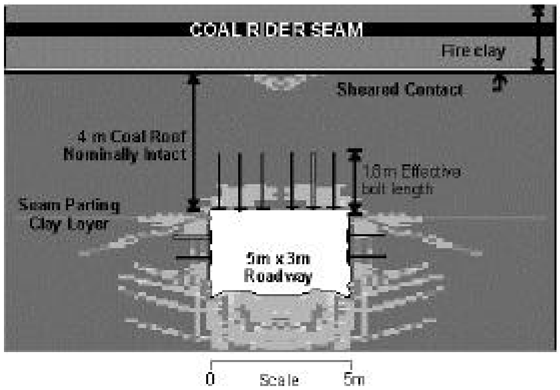


Fig 10(a)- Results of the FLAC modelling of 1800mm long 100% effective bolts.

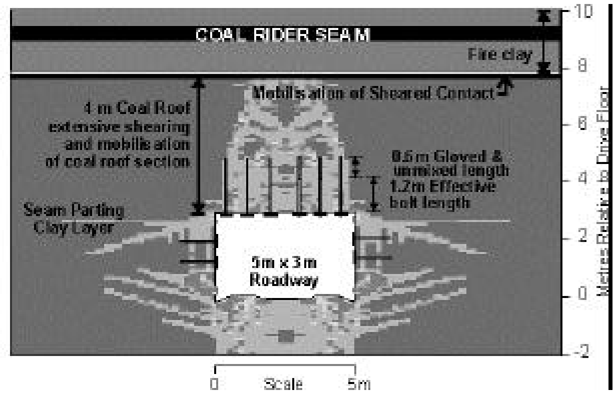


Fig 10(b) - Results of the FLAC modelling of 1200mm effective length, gloved roof bolts.

SUMMARY AND CONCLUSIONS

Investigation work has identified gloving and un-mixing of resin-grouted roof bolts as a significant problem, which occurs across a range of geological/geotechnical settings, and across the range of bolt/resin manufacturers.

Gloving was found over a wide range of bolt lengths, with the results showing anywhere between 30mm to 790mm affected. Typically the gloving affected around 500mm of the up-hole end of the bolt. The length of bolt affected by un-mixing also varied, with up to 750mm of bolt encased in un-mixed resin.

While the affects of gloved but mixed resin may be minimal, the un-mixed portion affords no reinforcement to the roof. The impacts of this can be assessed in two fronts, the first being with respect to health and safety, and the second being the economic cost. In terms of primary reinforcement dollars, this equates to 10% to 30% of the reinforcement dollars being of no benefit.

A mechanism, which accounts for the gloving and un-mixing phenomenon has been described, and validated by field trials and test bench trials and measurements.

The over pressurisation of the resin column as the bolt is spun up the hole results in the radial expansion of the cartridge and flattening of the hardener tube against the borehole wall. The bolt enters the expanded cartridge and does not shred the hardener tube, often resulting in a gloved and/or un-mixed section of bolt.

Nine bolt modifications and alternatives were tested across the range of geotechnical conditions, with the best results being achieved by the off-centre, Chamfer and a 200mm wiggled bolt, with the latter two being introduced as the standard bolt profile at one operation.

Numerical modelling was used to assess the impacts of gloving and un-mixing and showed that the shorter effective bolt length does have a significant affect on the design assumptions and stability of mine openings. In the case presented, the shorter bolts could not interact as a pattern and the reinforcement afforded to the roof was reduced, compared to the design assumption of 1800mm long bolts. The result being: an increased height of softening at lower levels of deformation, leading to the isolation and over stressing of the immediate and secondary roof sections. Following the results from the modelling a review of the Strata Management Plan was required to incorporate the findings, and a review of all monitoring data was required to reassess the requirements for secondary support.

Strain gauge bolts have been used to assess the loading characteristics of the gloved and un-mixed bolts, and may provide a means of assessing gloving, ROM, on a regular basis as part of an audit process.

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