13th CONFERENCE ON GROUND CONTROL IN MINING

Operational Experience with FLEXIBOLT Systems
in Australian Coal Mines

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ABSTRACT

Since the initial development and trials of FLEXIBOLT flexible roof bolts, further comparative testing and product development has been completed as part of the changeover to this roof support system at two Australian longwall operations, Ellalong and Angus Place Collieries. Details of the practical implementation of FLEXIBOLTS at both collieries are outlined together with their impact on roadway development rate productivity.

At Ellalong where fully encapsulated 2.1 m long bolts are used, the reduction in bolt density is discussed with respect to both support system design and work force acceptance. The impact of shear deformation on bolt loading is described.

Bolts longer than the working height have been required at Angus Place to achieve a suitable bolt anchorage horizon. Details of the long hole drilling and the benefits of a two stage grouting procedure are outlined. Improvements in roof conditions which have resulted from the inclusion of FLEXIBOLTS into the overall roof support strategy at Angus Place are described. Their importance to the viability of the Angus Place operation is also highlighted.

INTRODUCTION

The concept, development and initial testing of the FLEXIBOLT flexible roof bolt (the FLEXIBOLT) have been outlined previously in Ref 1. Since then the FLEXIBOLT has become a commercial reality with ANI Arnall being granted the first licence to manufacture and market the product. A number of underground longwall operations in Australia have introduced the FLEXIBOLT into their operations but Ellalong and Angus Place collieries which were actively involved in the initial bolt testing and development have been major users. As part of the introduction of the FLEXIBOLT into their development support strategies both mines have had to address such issues as assessment of the ground control and development benefits which could be realised by use of the FLEXIBOLT, workforce and union acceptance of the new concept and the development of installation procedures.

This paper describes the various stages of practical implementation of FLEXIBOLTS into both Ellalong and Angus Place and the results achieved to date.

ELLALONG COLLIERY

Ellalong colliery is a longwall mine operating near Cessnock in New South Wales (Figure 1). The longwall is currently operating at a depth of about 500 m. Ellalong has traditionally suffered from a difficult ground control environment due to a high (>40 MPa) insitu horizontal stressfield (Ref 2). Shear of the immediate roof strata has been identified as the principal deformation mechanism (Ref 3). Following on from an initial small scale trial (Ref 1) a larger scale trial of the FLEXIBOLTS has been conducted.

Major Performance Trial of FLEXIBOLTS at Ellalong Colliery (Ref 4)

Aims

The main aim of the trial was to compare the roof behaviour of a cut-through supported with reduced densities of FLEXIBOLTS with that in an adjacent cut-through supported with the standard density of rigid bar (AX grade)1 roof bolts. The secondary aims were to further assess workforce acceptance of the product and any installation, transport and handling issues which might arise.

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1 AX is the brand name of a rigid bar roof bolt manufactured by ANI Arnall which has a nominal yield load of 23 tonnes and a nominal UTS of 34 tonnes.
Bolting Patterns and Installation

The FLEXIBOLTS were installed in cut-through 12 on the maingate side of longwall 10 (Figure 2). The maingate belt road was developed with a Joy 12CM20 and a mobile boot end whilst the trackgate road and the cut-throughs were developed with a Joy 12CM5. The 12CM20 was equipped with 4 drill rigs mounted behind the cutter head and installed an 8 bolt pattern whilst the 12CM5 was equipped with two bolters behind the cutter head and an articulated bolter on the cutter head itself; each side bolter installed two bolts and the central bolter installed three bolts to give a 7 bolt pattern. The support pattern installed in cut-through 12 is shown in Figure 3. It had originally been intended to support cut-through 12 solely with FLEXIBOLTS but owing to a shortage of prototype bolts, the breakaway from the trackgate and the entry into the belt road were supported with conventional X-bar bolts (of which AX is one available brand). The strap spacing in the centre of the cut-through was dictated by a roof roll which required a higher density of support than had originally been intended. Installation of the 2.1m FLEXIBOLTS in 28 mm diameter holes proved to be straightforward with a 330 mm “fast” cartridge and an 880 mm “slow” cartridge. Some installations were tried with 27 mm holes and although installation was achievable, it was generally slower than with the 28 mm hole and (with the non-automated rigs) required a greater degree of care to prevent the bolts from flexing too much during installation. The adjacent cut-through, cut-through 13, was supported with 2.1m AX bolts at the standard pattern of 7 bolts per strap with straps at 0.8 to 1.0 m spacing. The roof lithology of both cut-throughs was similar with a 0.5 to 0.7 m coal roof being left below a 10 to 12 m thick band of relatively weak (UCS = 20 MPa), coarse, micaceous sandstone which formed the immediate roof of the Greta seam (the extracted seam).

Instrumentation

The zones featuring different support types were similarly instrumented with sonic probe extensometers to measure roof movement and strain gauged X-bar bolts to monitor bolt load response to this movement. Instrumentation was installed as near to the development face as could be practically achieved. Four extensometers were installed along the centreline of cut-through 12 (Figure 4) and data was also available from an extensometer installed on the ribline by Australian Coal Industry Research Laboratories (ACIRL) as part of an independent research project. The extensometer reference points were located approximately 7.0 m above the roof line. An extensometer was also installed in cut-through 13. Two of the extensometers showed random offsets (“glitching”) in successive readings almost immediately and so the data from these was disregarded.

Unlike rigid bar bolts the FLEXIBOLTS cannot be directly strain gauged. Therefore the load developed in the FLEXIBOLTS in response to the roof deformation could not be directly measured. To overcome this problem
Longwall 10, Cut-through 12

Approx extent of development fall
Position of roof roll

Notes
1/ All bolts 2.1m long.
2/ Strap spacing approximately equivalent to as installed.
3/ All straps were identical but those with FLEXIBOLTS are shown wider for clarity.

Figure 3. FLEXIBOLT Support Layout, Longwall 10, Ellalong Colliery

Legend

□ = Extensometer
● = Instrumented Bolt
#? = Site/Ext/No/Bolt No.

Figure 4. Instrumentation Layout, Longwall 10, Ellalong Colliery
instrumented X-bar bolts were installed in both cut-through 12 and cut-through 13 in addition to the normal bolting pattern. The loads recorded on these bolts were taken as being an index of the loads being developed in each FLEXIBOLT zone in cut-through 12 and the standard X-bar bolt pattern in cut-through 13. Difficulties were encountered reading some of the instrumented bolts due to the effect of the acid mine water on the electrical contacts.

Results for the instrumented bolts and the sonic probe extensometer are shown in Figures 5 and 6.

**Results and Conclusions**

At the X-bar site (cut-through 13) the total measured roof deformation was in excess of 120 mm when the longwall face was still 15 m inbye of the cut-through. The majority of this deformation occurred within the bolted horizon whereas in cut-through 12 (the FLEXIBOLT site) the total deformation was approximately 60 mm with the face 12 to 14 m inbye of the cut-through. Of the 60 mm total deformation, 35 to 40 mm occurred above the bolted horizon and only 20 mm total deformation in the bolted horizon.

The retreat of the face from 15 m to 5 m inbye of cut-through 13 induced a further 22 mm of movement in the bolted horizon. In cut-through 12 the ribline extensometer indicated a further 10 mm of displacement as the face retreated from 12 m to 4 m inbye of the cut-through: the centreline extensometer indicated 5 mm of displacement between the 0.4 m and 2.1 m horizons, but 60 mm movement below the 0.4 m horizon. This large movement in the immediate roof did not result in a high measured bolt load and no significant additional plate loading or deformation was apparent. Therefore it was concluded that this apparent movement was either highly localized or was artificial and caused by slip of the reference anchor in the hole.

Following discussion with the colliery management the following conclusions were drawn:

- the FLEXIBOLTS, at reduced densities, restricted roof movement in the bolted horizon to lower levels than the X-bar bolts;
- the restraint of movement in the bolted horizon by the FLEXIBOLTS is believed to be the reason why less deformation occurred above the bolted horizon in the FLEXIBOLT supported areas compared to the X-bar bolt supported areas;
- the ground stability achieved with 4 or 5 FLEXIBOLTS per strap was at least equivalent to that achieved with 7 X-bar bolts per strap at an equivalent strap spacing, and
- the roof deformation that should occur if 4 or 5 FLEXIBOLTS per strap were installed in the maingate (preferred stress direction) should be less than the deformation measured in the cut-through (worst stress direction).

**Shear Behaviour of Rigid Bar Bolts**

As part of the process of introducing FLEXIBOLTS into the mine as primary support, the management of Ellalong colliery decided to familiarise the workforce check inspectors and representatives with the effect of shearing in the roof on both conventional rigid bar bolts and FLEXIBOLTS. The initial part of the process was to make the workforce aware of the previous shear testing (Ref 1) which demonstrated the characteristic shear load vs shear displacement behaviour of the two bolt types. The second part was to demonstrate to the workforce how shear deformation of a rigid bolt could induce tension in the bolt and thus how a significant portion of a rigid bar's tensile capacity can be taken up even though no axial force has been directly applied. To do this a direct shear test was performed on a resin grouted portion of X-bar bolt which had been strain gauged to measure the induced axial loads at various distances from the shear plane with progressive shear movement. The results of the test are shown in Figure 7. The vertical axis shows the induced axial load, calculated from the strain gauge output, whilst the horizontal axis shows the distance of the strain gauges from the shear plane; each line on the graph represents a level of applied shear force (5, 10, 15 and 20 tonnes). The results indicate that an applied shear force of only 5 tonnes is able to induce an axial load (20 tonnes) approaching the yield load (nominally 22 to 23 tonnes) within 25 mm of the shear plane. The axial load level only becomes equivalent to the applied shear force some 125 mm from the shear plane. Increasing the applied shear force to 10 tonnes induces a load of 34 tonnes at the point 25 mm from the shear plane. This is the nominal ultimate tensile capacity of X-bar bolts. At this stage the bolt is indicated to be at yield axially 60 mm either side of the shear plane. Progressively increasing the shear load to 15 tonnes and beyond induced higher axial loads over an increasing bolt length.

This test demonstrated to the workforce how the mine's conventional roof support system would perform when subjected to shear and why the non-yielding FLEXIBOLT at reduced densities would be appropriate for Ellalong roof conditions.
Figure 5. Instrumented Bolt Results

Figure 6. Typical Sonic Probe Extensometer Results
Traditionally, active secondary reinforcement at Ellalong consisted of 10 m long 14 strand birdcaged cable bolts grouted with thixotropic cement grout. The effectiveness of long tendon reinforcement systems has been questioned on a number of occasions as major falls have been experienced in cable bolted roof. The development of the FLEXIBOLT has provided an opportunity to trial a higher density mid length secondary support system (2.1 m - 4.0 m) that can be installed with conventional bolting machines. For the first time at Ellalong a longwall take–off cut–through has been secondary reinforced with only 2.1 m long FLEXIBOLTS in conjunction with the primary support of X–bar bolts. At the time of preparing this paper the take–off road was showing a high degree of stability under elevated stress levels from the adjacent longwall.

In the future, with the superior reinforcement capabilities of the FLEXIBOLTS and total replacement of the X–bar bolts, it is hoped that there will be reduced requirement for the expensive and resource consuming long tendon reinforcement systems.

ANGUS PLACE COLLIERY

Angus Place Colliery is a longwall mine operated by Powercoal Pty Ltd, a wholly owned subsidiary of Pacific Power, the government owned NSW electricity generator. The mine is located at Wallerawang near Lithgow (Figure 1) on the western side of the Blue Mountains which form part of the Australian Great Dividing Range. The longwall currently being extracted is Longwall 19 at an approximate depth of 330 m below surface. Longwalls 16, 17, 18, 19 and the planned longwalls 20 to 24 occupy a portion of the mine lease where the Lithgow seam (the extracted seam) is immediately overlain by the Lidsdale seam. This is an inferior coal seam which is approximately 2.5 to 3.0 m thick interspersed with numerous stone bands some of which are very weak. It is influenced by major geological structures which are believed to be associated with Graben basement features. The thick coal roof created by the Lidsdale seam and the structured ground resulted in extremely difficult development conditions in Longwalls 16, 17 and 18. The delays caused by the poor conditions led to the trials with the FLEXIBOLT and its introduction into the development of Longwall 19.

Development Conditions in Longwalls 16 to 19

Angus Place Colliery experienced extreme difficulties in the development of the gateroads for longwalls 16, 17, and 18 and the start of longwall 19. The original support pattern in longwall 16 consisted of 5, 2.1 m long AX bar bolts per metre but the conditions soon dictated that this be upgraded to 12, 2.4 m long AX bolts plus rib–bolting. The extra bolts were required owing to the reduced bolt performance: typical short embedment pullout tests (150mm resin cartridge) gave values of 16 to 21 tonnes

Production Application of FLEXIBOLTS

After the successful trial of the FLEXIBOLTS and an extensive workforce training program, Ellalong placed an order to replace the existing X–bar bolts early in 1994. Specifications for the nut assembly were changed to a simpler and less expensive unit capable of withstanding a minimum 20 tonne head load. This specification was considered adequate to withstand the loads that would be generated in the short unbounded section of the bolt. Full encapsulation at Ellalong is generally difficult to achieve due to loss of resin in pre–existing shears.

On trialing the commercial version of the bolt, problems were experienced with violent failure of the nut soon after installation. All FLEXIBOLTS at this time were withdrawn from service. The nut failure problem was due to excessive brittleness caused by the hardening process. A new longer, less brittle nut has recently been tested underground and proven successful. The new FLEXIBOLTS will be available in June 1994 at which time the gateroad development at Ellalong will be converted from X–bar bolts to FLEXIBOLTS.

FLEXIBOLTS with the high strength cone nut have also been trialled as secondary reinforcement in areas where high longwall abutment stresses were anticipated.
in the higher stone roof but only 5 to 10 tonnes in the immediate coal roof. Even with the increase in roof support density and a number of further measures, roof falls still occurred.

The history of longwall 18 is a typical example of the nature and scale of the problems. During the development of longwall 18 two falls occurred on development with an additional five falls occurring due to stress notching as the longwall retreated. The increase in primary roof support failed to produce stable roof conditions so additional measures had to be taken. In the development of longwalls 16 and 17 extensive use was made of "Top Hat" heavy duty steel mine beams which were supported by timber legs. The setting of the "Top Hat" mine beams was extremely arduous and labour intensive and their use did not create satisfactory conditions. They also required the full face continuous miners to be dismantled so they could be retreated past the legs. Polyurethane injection (PUR) and the setting of timber chocks in the intersections was also common.

Following the failure of the "Top Hats" to create stable conditions, periodic cable bolting was introduced. After an interval of between 1–2 weeks the development section was stopped, the roadway was supported with centre legs and then cable-bolstered. A 24 hour cure period for the cement grout had to be allowed prior to recommencing development. This process took 2 to 3 days on average and the overall effect of these additional support and remedial measures was to reduce development rates from 10m per shift to less than 4m per shift. The length of each longwall block was reduced to allow continuity of production. Roof falls which occurred in the main gates also caused extensive delays with, typically, one week being required to clear a fall and recommence full production. The slow development and slow retreat rates also exacerbated delays with longwall change overs: delays allowed poor conditions to worsen resulting in reduced height and restricted access. This has created problems re-equipping the new face and has even necessitated turning chocks on to their sides in order to be able to move them onto the face.

Application of FLEXIBOLTS at Angus Place Colliery (Ref 5)

The broad aim of using FLEXIBOLTS at the Angus Place was to take advantage of the fact that bolts longer than headroom could be installed so that roof stability could be achieved economically. The intention was to install a 4.1 m long bolt to achieve a sound anchorage above the Liddell seam and to reinforce a thicker layer of the weak material and thereby create an acceptable degree of roof stability. Before FLEXIBOLTS could be introduced as part of the mine development primary support system, safe installation procedures had to be developed and basic performance criteria had to be established.

Installation Procedures

The major issues to be resolved on the installation procedures were the drilling of the 4.1m long hole and the FLEXIBOLT installation with hand held drilling machines. With regard to drilling the holes it was recognised that conventional coupled drill strings in the 19 or 22mm hex. size with standard metric threads requiring spanners for coupling and uncoupling would not be suitable for production use due to the time it would take to couple and uncouple the drill steels. Initial trials were carried out using a drill steel designed by ANI Arnall. This utilized a series of drill rods each of which had two male ends with a coarse square formed thread, which were joined with slightly oversize female couplers. The thread form was designed to allow the steels to be rapidly coupled and uncoupled by hand. Some minor problems were encountered uncoupling the steels but the problems which caused the greatest delays were leaks through the joints which reduced flushing pressure at the bit causing it to become clogged in clay bands. There was also a tendency to lose couplers. This drill steel proved to be the most acceptable for drilling a consistent 28mm diameter hole. Later, different drill steels were developed for drilling holes which had to be reamed to a larger diameter in the lower portion.

Initial installation trials were conducted to determine the length of resin cartridge which could be used when 4.1 m long FLEXIBOLTS were installed with hand held equipment. These also allowed the colliery management to determine safe working practices for FLEXIBOLT installation. The trials demonstrated that with hand held equipment it was possible to install the FLEXIBOLT through a 900 to 1000mm long chemical cartridge but the installation was difficult owing to the lack of lateral movement control on the drill and the flexibility of the bolt. This problem was overcome by fitting a tubular steel sleeve over the bottom 1.1m of the bolt to increase its rigidity. The addition of the steel tube caused the bolts to behave more like a rigid bar bolt during installation and allowed the bolt to be safely and quickly installed with a hand held machine by a single operator. Using a 1000mm chemical cartridge, the resin encapsulation length of the 4.1m long bolt was in the range 1500 to 1700mm, thus leaving an effective free length of 2.3 to 2.5m. The use of the steel tube required the lower portion of the hole to be reamed to 42mm. Eventually the tube was replaced with a short friction bolt and the hole was reamed to 55mm to allow post-grouting of the free length of the FLEXIBOLT.

Anchor Performance of Point Anchored FLEXIBOLTS and Potential Bond Strength for Post Grouted Section

As an extension to the initial laboratory and insitu bond strength testing (Ref 1) site specific bond testing was carried out at Angus Place to test the bond performance and ultimate bond strength of point anchors with different resin encapsulation lengths. The aim was to establish what length of point anchor was required to achieve the
ultimate capacity of the bolt and how hole size and bond length influenced both the bond strength and the bond stiffness. Unlike the previous in-situ tests where untwisting of the free-length was restricted by a steel sheath, these tests were conducted with standard non-sheathed FLEXIBOLTS so that the influence of any untwisting would be included in the test results. The format of the first phase of testing and results are shown in Table 1 (Ref 6). The conclusions drawn from these tests were:

- For short bond lengths the FLEXIBOLTS achieved pullout loads typical of those for AX bolts tested in similar strata at Angus Place.

- The peak pullout loads achieved by the point anchors was sustainable with further displacement.

- The anchor length achieved with a 1000mm long cartridge was adequate to give a nominal pullout load of 48 tonnes.

Table 1. Phase 1 In-situ Pull Testing of Point Anchored FLEXIBOLTS at Angus Place Colliery

<table>
<thead>
<tr>
<th>Test</th>
<th>Bolt Length (m)</th>
<th>Nominal Hole Length (m)</th>
<th>Cartridge Type Length(cm)</th>
<th>Nominal Bond Length (mm)</th>
<th>Estimated Bonded Horizon (m)</th>
<th>Peak Pullout Load (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.6</td>
<td>3.0</td>
<td>Fast 150</td>
<td>220-250</td>
<td>2.75-3.0</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>3.6</td>
<td>3.0</td>
<td>Fast 150</td>
<td>220-250</td>
<td>2.75-3.0</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>3.6</td>
<td>3.0</td>
<td>Slow 1000</td>
<td>1500</td>
<td>1.5-3.0</td>
<td>48</td>
</tr>
<tr>
<td>4</td>
<td>3.6</td>
<td>3.0</td>
<td>Slow 1000</td>
<td>1500</td>
<td>1.5-3.0</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>5.0</td>
<td>4.4</td>
<td>Medium 330</td>
<td>500</td>
<td>3.9-4.4</td>
<td>32**</td>
</tr>
<tr>
<td>6</td>
<td>5.0</td>
<td>4.4</td>
<td>Medium 330</td>
<td>500</td>
<td>3.9-4.4</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>5.0</td>
<td>4.4</td>
<td>Slow 1000</td>
<td>1500</td>
<td>2.9-4.4</td>
<td>48</td>
</tr>
<tr>
<td>8</td>
<td>5.0</td>
<td>4.4</td>
<td>Slow 1000</td>
<td>1500</td>
<td>2.9-4.4</td>
<td>48</td>
</tr>
<tr>
<td>9</td>
<td>5.0</td>
<td>4.4</td>
<td>Two Speed 1600</td>
<td>1500</td>
<td>2.9-4.4</td>
<td>N/T</td>
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</table>

Notes: * Maximum load limit of jack ** This test reached the limit of jack travel at 24 tonnes, the jack was reset and spacers inserted with the test proceeding to the ultimate peak load.

All tests conducted in 28mm holes

The second phase of pullout testing examined the influence of hole diameter and bonded horizon on bond performance. The test program is summarized in Table 2 and the results are shown in Figure 8 and summarized in Table 3 (Ref 7). The results show that both bond horizon and hole diameter have a significant impact on the performance and capacity of the point anchor. Comparing the results from 29mm holes at different bond horizons shows that significantly higher (30%) peak loads are achieved in the upper horizon. This is thought to be due to the upper bond horizon being at least partially in stone whereas the lower horizon was likely to

Table 2. Phase 2 In-situ Pullout Program

<table>
<thead>
<tr>
<th>Test</th>
<th>Bolt Length (m)</th>
<th>Assumed Bonded Horizon (m)*</th>
<th>Free Length (m)</th>
<th>Hole Diameter**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.1</td>
<td>2.2 to 3.4</td>
<td>2.58</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>4.1</td>
<td>2.2 to 3.4</td>
<td>2.58</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>3.6</td>
<td>1.7 to 2.9</td>
<td>2.02</td>
<td>29</td>
</tr>
<tr>
<td>4</td>
<td>3.6</td>
<td>1.7 to 2.9</td>
<td>2.03</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>3.6</td>
<td>1.5 to 2.9</td>
<td>1.90</td>
<td>28</td>
</tr>
<tr>
<td>6</td>
<td>3.6</td>
<td>1.5 to 2.9</td>
<td>1.90</td>
<td>28</td>
</tr>
</tbody>
</table>

* Assumes 10% loss of resin ** Diameter of top 1.5m of hole

Figure 8. Phase 2 Pullout Test Results

Table 3. Results of Phase 2 Pullout Program

<table>
<thead>
<tr>
<th>Test</th>
<th>Peak Load (tonnes)</th>
<th>Total Displacement (mm)</th>
<th>Mean Pullout Load (tonnes)</th>
<th>Mean Pullout Displacement (mm)</th>
<th>Mean Secant Stiffness (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>39.6</td>
<td>35</td>
<td>42.3</td>
<td>36.5</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>45.0</td>
<td>42</td>
<td>42.3</td>
<td>36.5</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>33.0</td>
<td>19</td>
<td>32.2</td>
<td>26.5</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>51.4</td>
<td>34</td>
<td>45.0</td>
<td>27.8</td>
<td>1.6</td>
</tr>
<tr>
<td>5</td>
<td>48.5</td>
<td>23</td>
<td></td>
<td></td>
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<tr>
<td>6</td>
<td>43.4</td>
<td>32.5</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
have been in coal. Tests 5 and 6 compared the performance of FLEXIBOLTS at the lower horizon in 28mm holes with those in 29mm holes. The peak loads in the 28mm holes were nearly 40% higher than those in the 29mm holes and the overall pullout stiffness was nearly 30% greater with this smaller hole size. Once again the FLEXIBOLT was able to maintain the peak pullout load with increased displacement.

At the time of these pullout tests extensometer monitoring of roof movement in an area supported with FLEXIBOLTS installed in 29mm holes in longwall 19 indicated strain levels in the free length portion of the FLEXIBOLTS to be of the order of 4%. At this strain level there is potential for tensile failure of the FLEXIBOLT. However there was no evidence of bolt failure. The pullout test results indicate that the peak load capacity of the point anchor in 29mm holes is likely to be less than the ultimate tensile capacity of the bolt so that when the bolt builds up a load greater than the anchor capacity, it will pull out. The ability of the FLEXIBOLT to maintain its pullout load with further displacement gives it the ability in this instance to function like a yielding type support and hence, high deformation levels can be accommodated by the point anchored system with a low risk of bolt failure.

The final phase of the bond strength testing conducted as part of the project involved laboratory tests of the bond performance of the FLEXIBOLT with cementitious grout (Ref 8). This was conducted to evaluate the potential benefits which might be gained by post-grouting the free lengths of the FLEXIBOLTS with a cement grout. The tests were conducted using a Portland 'A' type cement mixed at a relatively high water : cement ratio (by weight) of 0.45:1. It was anticipated that this grout mixture would be representative of a worst case, low grout strength situation. The tests were conducted in steel tubes of 40mm and 50mm internal diameter. Typical results are shown in Figures 9 and 10, and a comparison of the FLEXIBOLT pullout performance with that of "Birdcage" strand from Ref 9 is shown in Figure 11. The term "debonded Birdcage" strand refers to a 7 wire "Birdcage" strand which had the outer surface of the wires spray painted whereas "natural Birdcage" strand refers to a standard, 7 wire "Birdcage" product.

The results show that bond strength and bond stiffness both increase with reduced hole size: the behaviour mimics that of roof bolts grouted with resins. The overall conclusion was that the bond performance of the FLEXIBOLT with the Portland 'A' grout was sufficient for there to be merit in pursuing the development of a post-grouting system.
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Insitu Evaluation of FLEXIBOLT Flexible Roof Bolts - Following the successful development of a satisfactory installation system and evaluation of bond performance, a mid-length tendon system using FLEXIBOLTS was introduced as part of the primary roof support system of the longwall 19 maingate development. The standard primary roof support system generally featured 12, 2.4 m long A/B grade bolts per linear metre comprising 6 A/B grade bolts per W-strap at a strap spacing of approximately 0.5 m. With the introduction of the FLEXIBOLTS this was modified slightly so that between alternate straps, three 4.1 m long FLEXIBOLTS were installed.

As part of this trial Angus Place undertook an intensive investigation of roof deformation behaviour with the different support systems in various locations (Ref 10).

The layout of the field trial site is shown in Figure 12. It extended from cut-through 11 up to cut-through 14. A total of 12 extensometer sites were established and monitored in the field trial area. Table 4 summarizes the location details and roof deformation recorded by each extensometer. The objectives of the trial were to establish:

- whether the use of FLEXIBOLTS in the primary support system could eliminate the need for secondary support to be part of the development cycle, and
- whether FLEXIBOLTS could provide sufficient reinforcement to the structured, thick, coal roof to prevent the need for any additional secondary support measures.

Figure 13 shows examples of the total roof deformation from different extensometers plotted against face advance. These show that, with the exception of extensometers A, F and L, the deformation profile stabilised. Extensometers A, F and L were all located at intersections and two of the sites, A and F, were strongly influenced by structure. Based upon experience in longwalls 16, 17 and 18 the Technical Services Department of Angus Place Colliery had established 100mm of total roof movement as the trigger for installation of secondary support. Only extensometers A, F and L exceeded this “trigger” value and then after a period of several weeks: this delay and localisation of problems allowed the remedial corrective measures to be undertaken quickly and away from the development face. Figure 14 illustrates the difference between two different remedial measures which were tested: the first, undertaken at the site of extensometer L involved the addition of more 4.1m FLEXIBOLTS. The continuing
### Table 4. Extensometer Installations Longwall 19 Maingate (Ref 10)

<table>
<thead>
<tr>
<th>EXT</th>
<th>ROADWAY TYPE</th>
<th>STRUCTURE TYPE</th>
<th>ROOF SUPPORT (see note)</th>
<th>ROOF HEIGHT (m)</th>
<th>TOTAL ROOF DISPLACEMENT (mm)</th>
<th>MAJOR STRAIN ZONES (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Intersection</td>
<td>Slacky-roll/Swilly</td>
<td>Flexibolts</td>
<td>2.8</td>
<td>118</td>
<td>0.7(%)2(%)2.8(%)2.8(%)</td>
</tr>
<tr>
<td>B</td>
<td>Heading</td>
<td>None</td>
<td>2.4m AX bolts</td>
<td>2.7</td>
<td>28</td>
<td>2.1(1%)</td>
</tr>
<tr>
<td>C</td>
<td>Heading</td>
<td>Strike-slip</td>
<td>Flexibolts</td>
<td>2.5</td>
<td>41</td>
<td>0.7(1%)2(1%)2.5(1%)</td>
</tr>
<tr>
<td>D</td>
<td>Cut-through</td>
<td>Slacky-roll</td>
<td>Flexibolts</td>
<td>2.5</td>
<td>33</td>
<td>2.5(2%)3(1%)</td>
</tr>
<tr>
<td>E</td>
<td>Intersection</td>
<td>None</td>
<td>Flexibolts</td>
<td>3.2</td>
<td>63</td>
<td>1.9(4%)4.5(1.5%)5.5(2%)</td>
</tr>
<tr>
<td>F</td>
<td>Intersection</td>
<td>Strike-slip</td>
<td>Flexibolts</td>
<td>3.2</td>
<td>100</td>
<td>1.6(2%)3(3.5%)5.8(3%)</td>
</tr>
<tr>
<td>G</td>
<td>Heading</td>
<td>None</td>
<td>Flexibolts</td>
<td>2.5</td>
<td>22</td>
<td>0.5(1%)1.8(2%)</td>
</tr>
<tr>
<td>H</td>
<td>Heading</td>
<td>None</td>
<td>Flexibolts</td>
<td>2.8</td>
<td>18</td>
<td>2.5(1%)4.2(1%)</td>
</tr>
<tr>
<td>I</td>
<td>Intersection</td>
<td>None</td>
<td>Flexibolts</td>
<td>3.2</td>
<td>55</td>
<td>0.7(1.5%)1.8(3%)2.5(1%)3.8(1.5%)5.0(1.5%)</td>
</tr>
<tr>
<td>J</td>
<td>Heading</td>
<td>Strike-slip</td>
<td>Flexibolts</td>
<td>3.0</td>
<td>38</td>
<td>1.5(1%)</td>
</tr>
<tr>
<td>K</td>
<td>Heading</td>
<td>None</td>
<td>Flexibolts</td>
<td>2.7</td>
<td>22</td>
<td>0.5(1%)1.6(1%)2.5(2.5%)</td>
</tr>
<tr>
<td>L</td>
<td>Intersection</td>
<td>None</td>
<td>Flexibolts</td>
<td>3.2</td>
<td>100</td>
<td>1.5(4%)3.0(8%)4.0(8.5%)5.0(1.5%)6.0(2%)</td>
</tr>
</tbody>
</table>

**Note:**
- *Flexibolts* roof support is 3 x 4m FLEXIBOLTS and 10 x 2.4m AX bolts per metre.
- *2.4m AX bolts* roof support is 12 x AX bolts per metre.

The upward trend of the graph, albeit at a reduced rate, shows that the additional FLEXIBOLTS were not able to totally curtail roof movement. This is not surprising since the height of roof softening was 6.0 to 6.5m at the time of installing additional support so the additional bolts were entirely within the softening profile. The second additional support measure tested at the site of Ext F, was 8.0m long twin strand cable trusses. These were anchored above the height of the softening profile and the deformation graph shows that stability was achieved within about 10 days of the trusses being installed. This delay period probably reflects the long cure times required with cement grouts and the relatively "soft" performance of cable trusses.

The conclusions made by Angus Place were that:

- The high axial and shear strength properties of the FLEXIBOLTS allowed the weak roof strata to be controlled even under the influence of high gravity loads and high in situ and mining induced stresses.
- 4.1m long FLEXIBOLTS could achieve a high strength "instantaneous" anchorage above the weak coal roof and due to their timely installation they were able to develop high loads early in the roof deformation cycle which greatly reduced the rate and magnitude of the deformation.
- The yielding property of the point anchor allowed the FLEXIBOLT to maintain control of the highly deformable roof by providing a continued high resistance.
- The FLEXIBOLTS have achieved their objective of eliminating secondary support from the development cycle. Although the need for secondary support has not been totally removed it has been very much reduced and the time at which its installation is required is now such that it is an outbye operation and hence does not impact on the rate of development.

**Ongoing and Future Developments at Angus Place**

Aspects of the current FLEXIBOLT system at Angus Place which could be improved include:

- Drilling – the greatest time component of the installation cycle is the drilling time.
- Installation with hand held equipment – this requires the protective sleeve and limits the length of the chemical cartridge: continued development of the hand held system will be required because it will still be needed in longwall faces and confined areas.
- Point anchoring – the long free length does not provide efficient reinforcement.

- Secondary support – some is still required.

Angus Place Colliery is currently trialing or is intending to trial a number of measures to overcome these deficiencies. With regard to drilling, the mine is currently evaluating a track mounted compressed air powered bolter which is able to use longer drill steels than the conventional hand held equipment and hence the number of drill passes is reduced. The machine also has guides which allow the FLEXIBOLT to be installed...
without the protective sleeve and hence the hole can be drilled full length at 28mm. Trials have indicated that drilling times can be at least halved using the new system: a complete installation with the current hand held system takes about 15 minutes whilst with the new system a time of less than 5 minutes is the aim for a complete installation. The new system is also intended to fully encapsulate a 4.1 m FLEXIBOLT with a single man operation. The colliery’s overall aim is to devise a roof support system which will allow the FLEXIBOLT installation to be taken out of the critical path by installing them away from the face without compromising their support performance. Current trials with pretensioned roof bolts are showing encouraging signs that a two stage cycle for development can be achieved. Pretensioning has been shown to slow deformation sufficiently to allow a split cycle approach to work. A second technique currently being investigated involves using a flexible drill train to automatically drill holes to any desired length.

The use of the track mounted, compressed air powered machine also provides the opportunity to increase the length of resin cartridge. The basis for this is to increase the encapsulation length of the 4.1m mid length tendons and to ultimately fully encapsulate the bolts. Development of the resin is also ongoing to produce resins with appropriate viscosity, spin and set characteristics.

For bolts which will be installed with hand held equipment or for FLEXIBOLTS longer than 4.1m there will still be a requirement to post grout the free length. Grouting the free length should improve bolt performance and may give sufficiently increased control of the roof to prevent the secondary support option being "triggered". Recent research (ACARP project 3025) has demonstrated that a thixotropic cement grout suitable for post grouting can be mixed and pumped in a practical way underground. Angus Place have since undertaken further development work and insitu pullout tests to determine which grouts will be most cost effective for the post grouting operation and to develop a mixer/pump which will be efficient to use in the production environment. A major limitation which has been overcome was the ability to pump thixotropic grout through an 11mm i.d. tube reliably and quickly. The development of an effective and efficient post grouting system will also increase the viability of using longer (>6m) FLEXIBOLTS rather than conventional cable bolting in situations where the 100mm "trigger" is activated. Long FLEXIBOLTS have advantages over conventional cable bolts by allowing "instantaneous" support through the chemical point anchor (up to the plate capacity), use of conventional installation equipment and reduced installation time. The rapid response and installation time of the FLEXIBOLT system meant that it could be installed in a time frame which allowed a 6m bolt to control the deformation whereas the delays in activating a cable bolting system meant that
the deformation profile developed to the stage where an 8 to 10m cable bolt was required. However if the free length of the FLEXIBOLT cannot be post grouted then the support performance of 6m FLEXIBOLTS may not be adequate and conventional cable bolting may be more cost effective overall. Angus Place Colliery are undertaking a field evaluation of 6.0m long FLEXIBOLTS used for secondary support. This initial trial has been judged to be successful in so far as a zone of highly stressed and highly structured ground has been mined through without delaying the longwall retreat.

CONCLUSIONS AND ONGOING DEVELOPMENTS

The overall conclusions relating to the introduction of FLEXIBOLTS at Ellalong and Angus Place collieries are:

- Ellalong Colliery has been able to develop its gate roads and main headings with bolting densities of 4 to 5 FLEXIBOLTS per strap as opposed to 7 or 8 rigid bar bolts per strap.

- Due to the superior reinforcement capabilities of the FLEXIBOLT, the bolting density at Ellalong will be reduced by 33%, which all things being equal, will provide a minimum of 20% improvement in development rates. The workforce has accepted this new concept not only for its superior reinforcement capabilities but also for the much needed improvement in development rates.

- Prior to the introduction of the FLEXIBOLT system and the associated monitoring, Angus Place Colliery did not have control of the mining environment. The poor performance of the conventional primary bolting system allowed such large amounts of roof deformation that even when intense secondary support was installed, it was not possible to regain control of the roof. The geotechnical advice to the mine at this time was to revert to a free standing steel arch support system. The introduction of the FLEXIBOLT to the gateroad primary support has allowed control of the roof environment to be regained. The monitoring system allows the control to be measured and remedial action to be taken quickly and cost effectively. This control over the roof environment has allowed the mining process to be continuous and reliable: at the time of writing Angus Place was operating above budget.

- Angus Place colliery has completed the drivage of the longwall 19 gate road and the longwall has retreated to cut-through 14 without a roof fall and without having to interrupt the development to install secondary support.

Amongst the ongoing developments are the refinement of the two stage grouting process for full encapsulation of long (4 to 6 m) bolts and the development of resins and installation systems to allow fully encapsulated bolts up to 4 m in length to be installed at the face.

ACKNOWLEDGEMENT

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