TRIAL APPLICATION OF POLYURETHANE RESIN IN AUSTRALIAN COAL MINES

By
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ABSTRACT

Polyurethane resin (PUR) is extensively used in almost all coal producing countries. On the local scene, PUR components suitable for underground application were selected and subsequently, trials were carried out at several coal mines.

This paper describes the work at Pikes Gully Colliery (S.P.R, Coal), where water flow rates of up to 4.5 m³ (1000 gallons) per minute, were reduced to 1-1.5 m³ per minute at the first stage of application. Subsequent trials were carried out at West Cliff Colliery (Kembia Coal and Coke). A variety of PUR chemical mixtures were tested in coal ribs and in the roof of intersections and roadways. The trial results are presented with all particular details. Using the PUR injection method, the roof, at the most difficult intersection, was stabilised and 'de-bonded' roof bolts were re-sealed.

At Pikes Gully and West Cliff Collieries, 2 tonnes and 3 tonnes of PUR chemicals were injected, respectively. The technique, primarily based on German experience (Bergwerksverband), was used by Delta Control Systems Pty. Ltd. ACTRL was closely associated with the trials, which were monitored by installation of the measuring stations.

INTRODUCTION

It is probable that Australian longwalls have the best performance of any coal mines on the world scale. Consequently, any interruption to production (currently in the order of 12 tonnes per operational minute) has been most detrimental to the productivity and cost of coal. Although mining engineers consider that downtimes, caused by mechanical problems (drum shearers, transport belts), are the most prevailing factors, the occurrence of roof fails and gate road instability have caused an average loss of one month's production in a year, in the longwalls.

Most possible modern means for preventing and dealing with roof fails have been experimented with, but injection of polyurethane resin into strata is poorly understood. For 20 years, the Bergbau-Forschung GmbH, West Germany, has studied the applicability of polyurethane (PUR) binding systems, as reported by Meyer. The polyurethane grout is produced from two components (Bevoden and Bevedol), mixed in equal proportions. PUR has found many applications in the U.S. coal mines. According to Dolzelle, it has the following properties:

(i) Low viscosity, enabling injecting of PUR into cracks (initiated or propagated).

(ii) Increase in volume that can be varied from a ratio of 1:1 to 1:12.

(iii) Super-fast (seconds) to prolonged hardening times.

(iv) Flexibility, ductility and excellent bonding (cohesive) properties, superior to polyester and cementitious grouts.

At present, more than 1000 miners are involved with operations carried out in West Germany. Nonetheless, only selected and well trained crews should handle the chemicals. In the U.S.A. consumption of the resins amounted to 544,000 kg in 1982, and 1,360,000 kg in 1983.

In Australia, after an attempt by Titan (1979), a successful application of the PUR by Arnalls Engineering, was recently reported from Angus Place Colliery by P. McCarthy (Newcom Collieries). A total of 1.6 t of PUR was used (15 kg in each 2 m long hole) to

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stabilise the break-down face coal, in Longwall 9.

The subsequent trials conducted at West Cliff Colliery were also unique in terms of Australian experience. Thanks are primarily due to Messrs. R. Russon, (Manager) and B. Andrews (Project Engineer), who organised underground trials. For the above trials, approvals were issued by the Department of Industrial Relations.

BRITTLE ROOF AND HIGH STRESS FIELD

As generally experienced in Australian coal mines, shearing and bed separation rapidly propagate in the roofs, exhibiting a highly brittle fracture behaviour.

In the Bulli seam at West Cliff Colliery, in 313, 474 and 475 Panels, partings and shears locally propagated upwards (to 3 m), following initial sagging of the immediate mudstone roof, as described further below. Subsequently, the main (1-8 m) roof, thus unsupported, moved downwards, increasing support loading. Due to the development of cracks and bed separations, performance of the roof bolts was adversely affected and more secondary supports needed to be erected. A similar situation was observed at South Bulli Colliery, as shown below.

In the main gate of Longwall 5 (Figure 1), between cut-throughs 30 and 31, logging of four up-holes, drilled for installations of the cable bolts, was carried out. Up to a 3.5 m roof height, cumulative fracture spacings of 78 mm, 79 mm, 77 mm and 115 mm were measured for each borehole. For comparison, at South Bulli Colliery, in the main gate of Longwall 206, values of up to 225 mm were measured.

PROPOSING TRIAL OPERATIONS

For the injection of PUR, several trial sites were selected at West Cliff Colliery, as shown in Figure 1. Reinforcement of the most difficult intersection in 301 Panel, at Site 1, was firstly suggested. When a drilling pattern for the holes and injection operation was proposed, two alternatives were considered. The first was to produce a pressure arch effect (Figure 2), being the German method (to minimise consumption of PUR). Secondly, the roof could be reinforced on the whole, from rib to rib and upwards, in an area denoted A, B and C in Figure 3. Considering the extent of damage (bed separations) in the roof, comprising brittle mudstone and interbedded sandstone, the latter method was found more appropriate (compared to more deformable and elastic strata in West

Fig. 1 - TRIAL SITES - WEST CLIFF COLLIERY.

Germany), as described in Section 4. Although essentially unnecessary, all the up-holes drilled in the roof (Sites 1) were injected in order to gain more experience with the capability of PUR.

Fig. 2 - REINFORCED ARCHED PROFILE.

TYPES AND PROPERTIES OF PUR

Originally formulated two-component chemicals, Bevedan and Bevedol, were developed into a considerable range of mixtures, suited to any type of the remedial work underground.

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Components (variety) of PUR, recommended for Australian coal mines and used in the trial operations, are given in Table 1.

<table>
<thead>
<tr>
<th>Type of PUR</th>
<th>Setting Time at 25°C</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>N or &gt; 120</td>
<td></td>
<td>Since expending is not excessive in both wet and dry rock, 'NK' is suitable for medium fractured ribs or roots.</td>
</tr>
<tr>
<td>S &lt; 90</td>
<td></td>
<td>'S' founds in dry rock, but more in wet rock. For example, once most damaged (wet) immediate roof is sealed, higher (dry) roof is reinforced. It exhibits a very high expansion, if injected into ground water.</td>
</tr>
<tr>
<td>WF &lt; 60</td>
<td></td>
<td>Called long-staying liquid, (strength up to 100 MPa). 'WF' is most effective in overstressed coal ribs (does not expand in dry ribs).</td>
</tr>
<tr>
<td>WFA &lt; 30</td>
<td></td>
<td>The fastest PUR available. Suitable for overstressed pillar corners and sealing off high water flows. Full strength is achieved in 30 seconds (reacts in 10 seconds).</td>
</tr>
</tbody>
</table>

Note: Components are mixed at a ratio of 1:1.

**IMPORTANT FINDINGS, SITE I**

These can be listed as follows:

(i) The roof exhibited cumulative bed separations of 0.31 m in a 4.5 m roof column (Figure 3). Individual partings were measured using a fibrescope. Because of the occurrence of sizeable cracks (partings up to 100 mm in width), it was decided to employ PUR.

(ii) Total volume \( V \) of 'voids' (represented by area of B, C, D in Figure 3), presumed to exist in the roof section of A, B and C, was calculated as follows:

\[
V = \frac{3 \times 6 + 3.5 \times 6}{2} = 6.1 \text{ m}^3
\]

Considered as being a triangular prism.

(iii) A volume of 1.5 m³ of the chemical mix was injected in 1.5 shifts. It developed approximately 4.5 m³ of expanded PUR. This expansion ratio (achieved by foaming agent) was considered by the German specialist (D. Lohse) as being adequate for this intersection. Injection pressures were very low. In one hole only, an intermittent increase in pump pressure of up to 100 bars (10 MPa) was recorded, indicating a complete 'saturation' and distribution of the resin upward and sideways.

(iv) After injecting the very first hole, PUR was found distributed to a roof area of over 20 m² (Figure 4).

(v) Twenty roof bolts amongst 50 in total were re-sealed. The least efficient (and de-bonded) bolts were re-engaged.

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Fig. 4 - PUR DISTRIBUTION SITE 1. ON INJECTING FIRST HOLE.

(vi) A minimum 1 m height was required for installation of packers within holes, above the highly disturbed immediate roof.

For the above (and subsequent) trial, a complex of geotechnical monitoring stations was installed by AGIRL, as described further below.

ROADWAY STABILITY, SITE 2

For Site 2 (C Heading, 313, between cut-through 12 and 13), the pattern of up-holes drilled in severely broken roof was modified (Figure 5) in accordance with the previous experience. The techniques used consisted of:

(1) Injecting 2 m holes in a V pattern (Figure 6) and sealing the immediate roof by a fast setting resin (S type), thereby reducing losses of PUR (dripping down through large cracks or along de-bonded bolts). For injection of the upper roof horizons (4.5 m holes), a NR mixture was applied. The latter of chemical exhibits a higher foaming capability (1:3) at a decreased strength, compared to the S type mixture (1:1 to 1:2).

In general, where relatively smaller cracks occur (compared to cut-through 3), Site 1, use of the NR mixture was found adequate.

(ii) Total volume of voids V, estimated to occur between the roof holes, spaced at 5 m (Figure 6) and within a 4.5 m roof column (Figure 5), was calculated as 3 m³. In comparison, approximately 0.8 tonne of the NR chemicals was injected, capable of expanding to a maximum volume of 2.4 m³. No increase in pump pressures was recorded, indicating an incomplete infusion operation.

(iii) Three holes, spaced at 5 m, drilled across the roadway (Figure 6), appeared to be adequate for a successful operation (in the case of Site 2).

Fig. 5 - RECOMMENDED PATTERN OF HOLES, SITE 2.

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Very high strength and flexibility was observed (at samples taken from the rib faces). The technique used could be described as follows:

(i) 180 kg of WF mix was injected into 5 holes.

(ii) Pump pressures ranged from 0.5 to 5 bars (50 t/m²). In the case of severely broken ribs, the pump pressures in excess of 5 bars could not be applied.

(iii) In three holes, packers were installed at 1.1 m depths. Alternatively, in 2 holes, bare injection pipes were used for the delivery of PUR. Sealed with a synthetic cloth, no leakage problem was experienced at the hole mouths.

(iv) Holes were positioned at mid-seam height, slightly inclined upwards. For the future application, holes would be spaced at 5 m and not at 3 m (as observed from the ability of PUR to spread).

Similar to previous sites, it appeared that, at Site 3, an incomplete injection operation had been carried out (200 kg – 250 kg of WF was applied). In contrast, the WF mix was successfully applied in more stable ribs in the travelling road, near QT 27 in 475 Panel, Site 4 (on completion of this report). At this site, the full rib saturation was achieved by injection of 20 litres of the mix per hole (grout distributed to a distance of 2 m from the holes). According to German experience, for extremely broken pillar ribs (especially corners), the type WFA, setting in less than 30 seconds, would be recommended.

MONITORING

Since it was expected that on infusion of the PUR, an increase in stresses (chemical pressures) could induce collapse of the roof, the following monitoring methods were used to safeguard the trial operations:

(a) Amongst several props installed under the roof (Sites 1 and 2), a Geokon stress cell was positioned beneath a prop, near a roof hole under injection. The prop load was measured via an electronic Ird stress readout unit, approved for underground use. A load increase of up to 1.5 tonnes which was recorded during the operation, remained unaltered after the injection operation. No damage to the roof was observed.

(b) Roof convergence varied from 1 to 7 mm. Amongst seven convergence measuring stations, only one recorded the convergence value of 7 mm, on injecting the first hole. This station exhibited an increase of 2 mm, after 3 days. These measurements were subsequently accompanied by a long-term monitoring of the roof levels, carried out by the mine’s surveyor. Practically, there was no movement in the roof (previously heavily sagging) after the injection operation, as shown in Table 2.

TABLE 2
CHECK POINTS OF ROOF LEVELLING – SITE 1 (m)

<table>
<thead>
<tr>
<th>Check Point</th>
<th>20/1/86</th>
<th>25/3/86</th>
<th>10/4/86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre</td>
<td>9802.058</td>
<td>9802.083</td>
<td>9802.058</td>
</tr>
<tr>
<td>1</td>
<td>9801.994</td>
<td>9801.999</td>
<td>9801.995</td>
</tr>
<tr>
<td>2</td>
<td>9801.834</td>
<td>9801.838</td>
<td>9801.833</td>
</tr>
<tr>
<td>3</td>
<td>9801.765</td>
<td>9801.747</td>
<td>9801.745</td>
</tr>
<tr>
<td>4</td>
<td>9801.989</td>
<td>9801.993</td>
<td>9801.990</td>
</tr>
</tbody>
</table>

Note:
1. Underground levelling within ± 5 mm.
2. 'Upward' movements on 25/3/86 within accuracy.

(c) Fibreoptic surveys, carried out in the up-holes, proved to be useful. According to Dalzell, they should always precede infusion of the holes.

(d) Core samples, obtained from the reinforced roof and coal ribs (Plates 1 to 4), were tested in the laboratory. Since the first 0.3 m and 0.1 m in coal ribs and roof, respectively, were badly broken, no cores were obtained from these initial sections. Coal samples, obtained from the injected ribs are...
shown in Plate 1 and roof samples, in Plates 2 to 4. Coal samples 1 to 4 (Plate 1) exhibited an uniaxial compressive strength (UCS) between 5.1 MPa and 13.8 MPa. Samples 5 to 7 failed at the same 9.5 MPa (compared to a 20 MPa UCS of the Bulli Seam). The coal samples exhibited a high residual strength (ductility behaviour after failure), indicating that the coal mass would be held together in the ribs (by PUR matrix), under the peak abutment loads.

Plate 1. COAL SAMPLES 1 TO 7.

Plate 3. SAMPLE FROM 1.6 m HORIZON.

Plate 2. SAMPLES FROM IMMEDIATE ROOF.

Plate 4. SAMPLE FROM 3.2 m HORIZON.

(c) A sample prepared from a continuous sandstone core (obtained from a 3.2 m horizon, Plate 4), exhibited a 79.0 MPa UCS and a 2.6 MPa tensile strength. This can be compared to a 29.5 MPa UCS (1.3 MPa tensile strength), obtained from a 'bonded' sample, exhibiting vertical and horizontal shears, as shown in Plate 3 (sample from a 1.6 m roof height).
SEVERE WATER FLOW AT PIKES GULLY COLLIERY

In addition to application for strata reinforcement operations, mixes of PUR, expanding at high ratios, have been used for sealing ground water. The following example is of a trial sealing operation, undertaken at Pikes Gully Colliery, where an inrush of water (4500 l/min) was detrimental to coal production of this mine.

Purpose of the trial, organised by Messrs. J. Conlon (Manager) and H. Newman (Project Mining Engineer), BP Coal, was to inject polyurethane (PUR) into rock and coal fissures at cut-through 9 A/B (Figure 8) and to seal or reduce a severe ground water flow.

History of Water Inflow

The mine has always experienced wet conditions, mainly in the roof at the Eastern District. Water inflow of 200 gallons (approximately 1 m³) per minute was measured during the mining sequence. This flow weakened the roof. Consequently, a roof fall occurred, trapping a continuous miner.

Although water coming from the roof at B10-11 gradually dried up, at B9, it continued flowing from the floor at a rate of approximately 200 gallons per minute (at C9, there was little flow).

For the above reason, development of the A Heading at the mine barrier pillar, was subsequently undertaken and in accordance with the mining sequence, it was followed by a back-boring into B9. When the latter heading (denoted 9A/B) was driven to a distance of 12 m (cutting towards a shear zone), an 0.75 m displacement was exposed in the floor at the driven face, releasing water at a flow rate of 1000 gallons per minute.

Measurements of the water flow rates continued on a regular basis. Analytical tests of the water samples, taken at the face of 9A/B, indicated almost pure H₂O (compared to H₂S content in the mine ground water). In addition, an examination of the mining and geological conditions was initiated, as described below.

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Method of Injection

A series of 43 mm holes drilled into the rib area surrounding the water outflows, as shown in detail in Figure 8 ('A' Face Section). The holes were drilled in such a pattern so as to allow a gradual seal of the broken strata. Rapid setting mixes (WF and WPA), capable of closing off high water flows, were suggested to be used in sealing operation. These chemicals react within 10-20 seconds and, in water, expand immediately. The operation was initially successful (600 kg of PUR was injected).

However, the water pressure was responsible for an increased water flow at B Heading, situated at a higher level (comparing to A Heading). Water was pushed up through the cracks, present in the floor. Later, a much more active pathway formed in the 'B' Face Section at 9A/B (detail in Figure 8). It was found impossible to seal such an extremely active zone at the 'B' Face, unless under the protection of relief holes (X and Y).

These were drilled above injection holes (Nos. 1 to 8) at a diameter of 125 mm, fitted with standpipes and control valves. Under the protection of these pressure-relieving holes, the sealing operation was accomplished. Overall, 1200 kg of PUR was injected.

As a result of the above operation was a reduction in the flow rates of approximately 2.5 m³ (600 gallons) per minute. Excess water quantity produced in B9 Heading, where the water level was rising, as mentioned above. For this reason, angled down holes, spaced at 1.5 to 2.5 m in length, were drilled in the floor of this heading, and sealed (60 kg of PUR). Consequently, the water flow of 4.5 m³ (1000 gallons) per minute was reduced to a steady flow rate of 0.1 m³ (230 gallons) per minute. (Locally occurring 'unstable' sections were not sealed by the time of completion of this paper).

CONCLUSIONS

(i) A considerably high volume of PUR (types 3, fast and 36, slow) was used at Sites 1 and 2 (West Cliff Colliery), owing to a significant volume of voids. Reduced chemical quantities would be required in the early stages. Fully grouted cracks as small as 0.1 mm were observed at the cores, obtained from the reinforced roof. Cost of reinforcing a linear metre of severely damaged roadway roof is estimated to be in the order of $800.

(ii) Type WF of the chemical proved to be very suitable for the stabilisation of severely broken coal ribs. This is the non-expanding variety (for a dry environment). Standard diameter of 43 mm is appropriate for the injection holes (spaced at 4 m to 5 m).

(iii) At Pikes Gully Colliery, it was demonstrated that water flows of as much as 1000 gallons (4.5 m³) per minute could be controlled by the PUR injection method. Due to the existence of a highly fractured area (goaf), when one area of the flow was sealed, water pressure found a relief at other points (levels).

(iv) Sealing operations, carried out in stages, were a typical feature of the experiment. High-pressure relief holes were found necessary for the successful infusion of PUR.

At this stage of research, it is recommended to conduct the following tests:

(a) Injecting PUR into pre-drainage in-seam holes (once captivation of the gas is completed) for stabilisation of the face coal in the completion lines of longwalls.

(b) Flame retardant 'Pyrol CE9' by Stauffer Co., burns at 2520°C. At a 50% volume in PUR, the mix is unable to sustain self-combustion, suggesting a safer use of the resins underground.
REFERENCES

