Surface Grouting of Circular Roadways

* By J. MARTIN, BSc(Hons)

INTRODUCTION

When it is required to place large quantities of grout below ground several advantages may be obtained by positioning the grout mixing equipment on the surface and conveying the mixed grout to the point of use by pipeline. These may be summarised as:

(i) No shaft time is used for the transport of bulk materials.

(ii) Emphasis below ground can be put on the correct placing of the grout, rather than the problems associated with its mixing and pumping.

At Shirebrook Colliery approximately 2000 m^3 of 30 MPa strength cementitious grout was used to backfill the annulus of 1000 m of 5.4 m diameter circular arched roadway within the Deep Soft Seam. This is equivalent to approximately 3500 t of bulk material, which would have required the transport of 1166 three tonne mine cars underground. The requirement in filling the annulus of the roadway was to reduce the possibility of point loading and resultant distortion of the circular arch. This has proved successful over the first two years and these roadways should have a long life without the need for any backripping or dinting operations.

In October 1988 Cementation Mining Limited (CML) was awarded the U26 development contract at Warsop Colliery. Part of this contract involved the establishment of a surface grout station to pump a 4 MPa grout mix over a distance of 3000 m to backfill the annulus of the circular roadways.

From experience of grouting from the surface the author now considers it to be an area where British Coal could make significant financial savings in the future.

1. THEORETICAL REQUIREMENTS

When it is intended to pump grout from the surface into a mine there are a number of interacting factors which must be taken into account:

(i) Grout fluidity.
(ii) Grout density.
(iii) Grout pumping life.
(iv) End use of grout.
(v) Placing rate.
(vi) Vertical drop.
(vii) Horizontal distance.
(viii) Overall pipeline length.
(ix) Pipeline diameter.
(x) Pipeline roughness.
(xi) Pipeline bends.

Consider the system shown in **Fig. 1**.

The major factors are considered in detail below:

1.1 Pump House Pressure and Flow Rates must be Realistic

The pump house pressure and flow rate are directly related to the static head and the pressure loss along the pipeline. The static head can be calculated from the difference in datum levels between each end of the pipeline. The pressure loss along the pipeline is more difficult to calculate and is dependent upon the fluidity of the grout, the pipeline diameter and the pipeline roughness. There are various theoretical analyses which can be carried out, but more realistic results can often be obtained by conducting surface pumping trials and developing an empirical relationship. Normally, pumping pressures of up to 7 MPa and flow rates of around (1×10^{-3}) m^3s^{-1} have been found to be realistic.

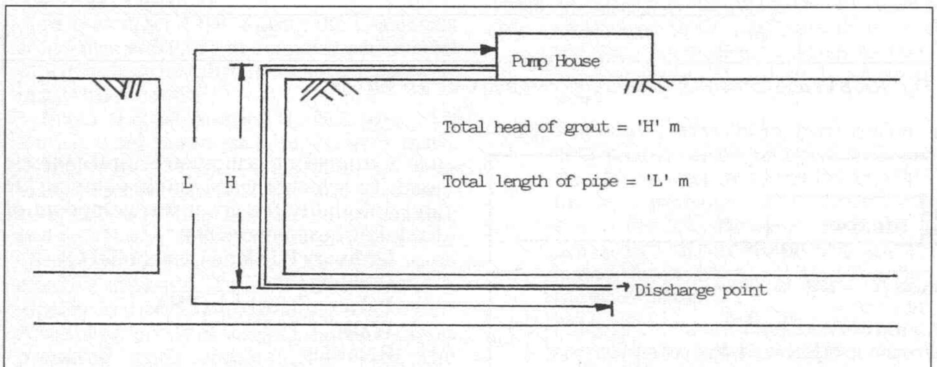

Fig. 1

1.2 The Grout must be Delivered in the Correct Formulation

If the pressure in the pipeline falls below the vapour pressure of water, approximately 2.34 kPa, then cavitation will occur. In this situation the grout will fall under gravity through the empty pipe and segregation of the components may occur. Therefore to ensure the grout is delivered as a uniform mix it is best never to let the pressure in the pipeline fall below atmospheric.

1.3 The System must not Create Blockages

There are two basic flow regimes possible in a pipeline, laminar and turbulent.

In laminar flow conditions there exists a thin stationary layer along the pipe wall and frictional losses are proportional to the velocity. This may cause a build-up with time when using grout mixes unless the pipelines are cleaned regularly. As the flow rate increases the flow regime passes through a transition zone and into turbulent conditions where frictional losses become proportional to the velocity squared. There is no stationary layer along the pipe wall in the turbulent flow condition. Therefore, to reduce the possibility of settlement occurring in the horizontal sections of pipeline the flow should be kept in the turbulent regime (see **Fig. 2**).

Without going into complex fluid mechanics formulae there is a relationship derived from the Froude number of flow for a system of mixed particle sizes:

$$V\,min = Fr\,\sqrt{2\,g\,D\,(S_s - 1)}$$

where V min = minimum velocity to prevent settlement (ms^{-1})
g = acceleration due to gravity (ms^{-2})
D = internal pipe diameter (m)
Fr = Froude number (ratio)
S_s = specific gravity of the solids ($kg\,m^{-3}$)

For cement based grouts, with a factor of safety of 1.5, the table shown in **Fig. 3** can be produced. It can be seen that the required flow rate to prevent settlement occurring can be quite high, depending on the pipe diameter chosen.

2. PRACTICAL EXPERIENCES AT SHIREBROOK COLLIERY

The system at Shirebrook Colliery is as shown in **Fig. 4**.

* Mr Martin is a Project Manager, Cementation Mining Ltd

Presented at the 1989 Junior Sections' Annual Meeting held on 16 May 1989 at the Cairn Hotel, Harrogate

MS received by IMinE 21.4.89

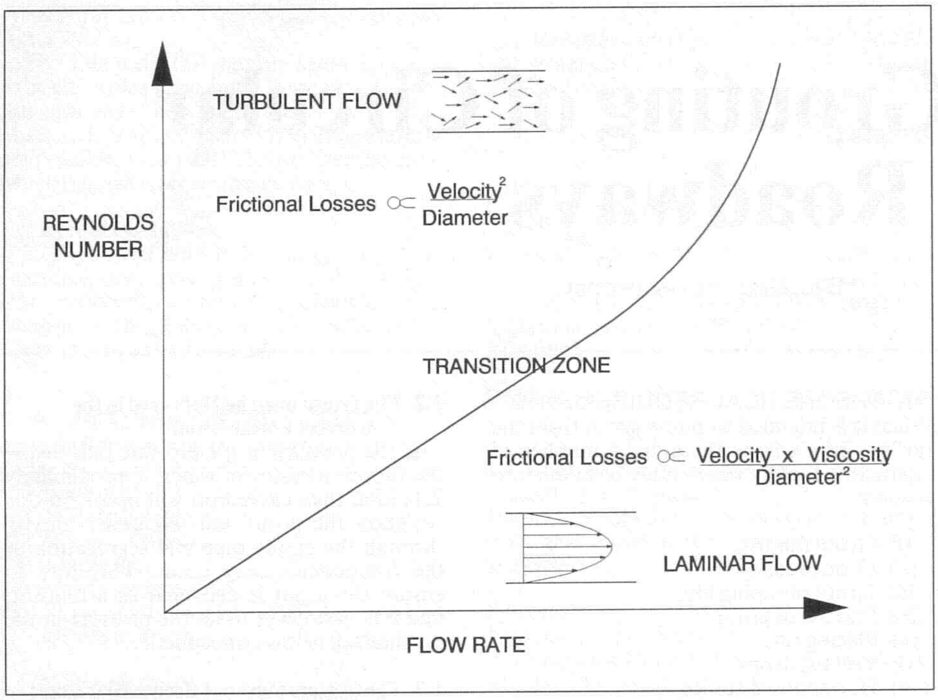

Fig. 2 Turbulent and laminar flow

Pipeline diameter (m)	Recommended minimum flow rate to prevent settlement in the pipelines (m^3s^{-1})
0.025	0.0011
0.038	0.0031
0.051	0.0064

Fig. 3 Table showing recommended minimum flow rates to prevent settlement in various diameters of pipeline.

2.1 System Design

It can be seen from **Fig. 3** that a pipeline diameter of 0.025 m would be required to prevent settlement in the horizontal sections for a cement based grout flowing at around (1×10^{-3}) m^3s^{-1}. However, to comply with the high grout strength specified a dense mix with a high cement content and low water: cement ratio had to be used. Pumping tests with this grout indicated a high pressure loss per unit length along a 0.025 m diameter pipeline at the required flow rate. Unfortunately this meant that the pump house pressures would have been excessive, even with the assistance of the shaft head. Therefore a compromise 0.038 m diameter pipeline was used. This enabled the pumping pressures to be reduced but the resultant flow rate was insufficient to prevent settlement. To overcome this problem a 'ferret' (wiper plug) was sent through the line every day after grouting to remove any build-up of settled grout.

Cavitation was not a problem at Shirebrook due to the type of grout and methods employed. Pump house pressures in the order of 4 to 8 MPa were normally recorded. In order to reduce frictional losses large radius bends and socket joints were used. The socket joints were designed to enable the ends of each pipe length to butt tightly together to reduce the possibility of a ferret becoming lodged at a joint. Union couplings were installed at specific points to enable the pipeline to be split if any problems arose.

2.2 Mix Design

As has already been stated the 30 MPa mix used is extremely strong for a fluid grout

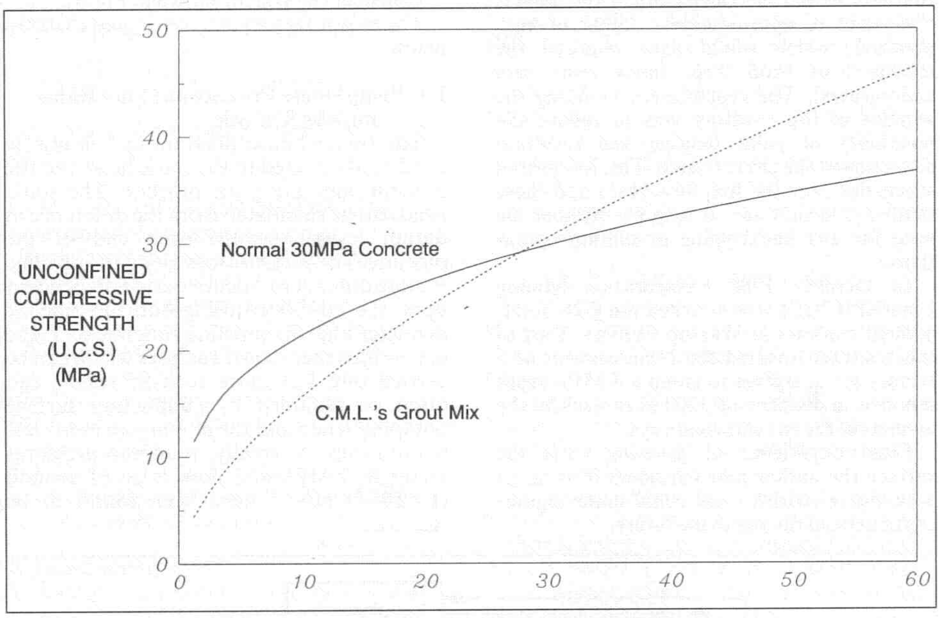

Fig. 5 UCS vs age for normal 30 MPa concrete and CML's grout mix

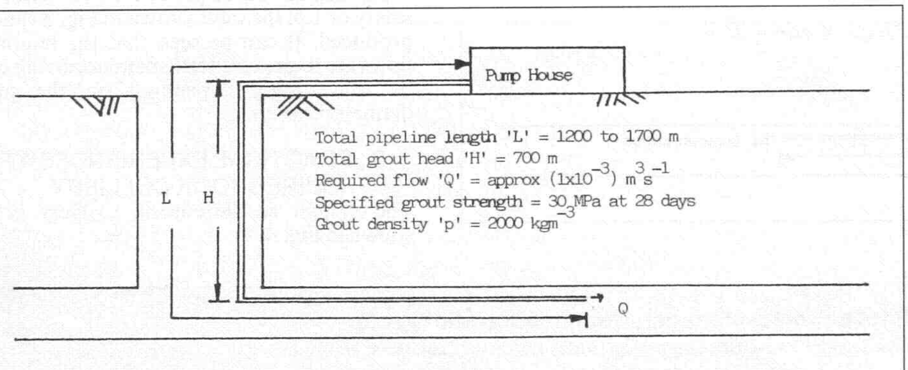

Fig. 4 Shirebrook Colliery system

and is equivalent to most structural concrete used. To achieve the maximum pumping life and flowability the grout was composed of the following components:

- Ordinary Portland Cement (OPC)
- Building sand
- Pulverised fuel ash (PFA)
- Water
- Retarder
- Super plasticiser

Due to the substantial PFA content strengths in excess of 50 MPa are being reached after one year (see **Fig. 5**).

3. PRACTICAL EXPERIENCES AT WARSOP COLLIERY

In October 1988 CML was awarded the U26

development contract at Warsop Colliery. The work involves approximately 1000 m of 5.0 m diameter circular arch drivage together with four junctions, all within the Deep Soft Seam. The annulus of these roadways has to be filled with a 4 MPa grout mix and it is envisaged that up to 2000 m^3 may be required. As part of its tender CML offered to install two shaft lines and to pump the grout from the surface. The saving in shaft time by not having to transport materials underground may have been instrumental in British Coal's decision to award the contract to CML.

3.1 Mix Design

The pipeline length at Warsop Colliery was too long to be drained and re-filled each day. In addition, the strength specified for the backfill grout was much lower than that specified at Shirebrook Colliery. These factors suggested that a grout based on the familiar two pipe pump-pack system would be more appropriate. Several such systems have been developed which exhibit extended pumping lives for the two separate components, combined with high fluidity and rapid strength development when mixed together. After surveying what the market had to offer the 'Hydropack 30' system manufactured by Blue Circle Industries was chosen. This has a pumping life of at least three days and reaches strengths of 6 MPa at seven days using a mix density of 1250 kgm^{-3}.

The Hydropack 30 system is composed of two components—'Packset' and 'Packbent' which are mixed together in a one to one ratio. The Hydropack 30 is pumped behind the sheeting using a modified Mono pump and gains its initial set in about 15 minutes.

To enable the mixed grout to stay behind the sheeting until it gains its initial strength a small amount of gelling agent is added. The aim is to form a thixotropic liquid which is pumpable but which will bridge small gaps in the sheeting. Larger gaps in the sheeting have to be sealed using 'Hardstop' or other similar material. One drawback of using the gelling agent is that it does reduce the UCS of the grout, although not below the 4 MPa specified.

3.2 Grout Pipes

In December 1988, during the Christmas shutdown, two 0.038 m diameter schedule 80 pipelines were installed in the downcast shaft in a 24 hour period.

From the pit bottom to 26's area two British Coal pump-pack pipes were made available to CML. These lines had previously carried the 'Tekcem' and 'Tekbent' components of the 'Tekpak' pump-packing system. Each 2300 m pipeline had to be tested prior to acceptance. One of the most effective methods of proving the bore of a pipeline is to send a ferret along with water. A series of ferrets of varying diameters were prepared and, commencing with the smallest, were sent through the pipeline. Unfortunately these pipelines had a significant coating of consolidated material and a number of lengths had to be changed. The Tekbent line was the simplest to clean out and prove while the Tekcem had a deposit of hard cement in the base which could not be removed. Eventually both lines were cleaned to an acceptable standard.

3.3 System Design

The highly fluid nature of the pump-pack grout components indicated that the problems would be the reverse of those at Shirebrook Colliery, ie too much static head and too much flow.

Again, from **Fig. 3**, for flow rates of (1×10^{-3}) m^3s^{-1} the pipeline diameter should be 0.025 m to prevent settlement. Unfortunately the pipelines are 0.038 m diameter and will therefore have to be cleaned with a ferret.

The pump house pressure can now be calculated:

Pressure head supplied by the grout
$$= \rho g h$$
where:
ρ = grout density (kgm^{-3})
$$= 1255 \times 9.81 \times 715$$
g = acceleration due to gravity (ms^{-2})
$$= 8.5 \text{ MPa}$$
h = static head (m)

Frictional losses along the line = approx 2.5 MPa (Very low due to the fluidity of the grout and the diameter of the pipeline). Therefore:
Pump house pressure = Pressure losses along pipeline − Pressure head supplied by grout
$$= 2.5 - 8.5 \text{ MPa}$$
$$= -6.0 \text{ MPa},$$
ie the system will cavitate.

In order to prevent the system cavitating and ensure the maximum flow rate is not exceeded a flow restrictor will be required at the end of the line.

3.4 System Operation

CML has been grouting at Warsop since January and has been pleased with the way the system has developed. Quantities of up to 200 m^3 have been placed in a ten shift working week. Listed below are some of the more interesting points:

(i) Flow restrictors are being used at the end of the lines to prevent cavitation and balance (regulate) the flow along the pipes.

(ii) The lines are being purged by ferreting every day.

(iii) The surface grout station now has automated material and water batching. This enables one man to produce up to 50 m^3 of grout per shift.

(iv) The pump at the surface is only used to charge the shaft line; from then on all the grout is syphoned down to U26's area, ie letting the shaft head do the work.

(v) Difficulties have been experienced in obtaining a valve which will withstand the abrasive action of the Packset 30 at the high pressures encountered at the end of the line. However, a number of heavy duty valves are on trial and it is hoped this problem will be overcome in the near future.

(vi) After about seven weeks of grouting a contaminated load of Packset 30 was delivered*. This had a much reduced pumping life and resulted in the loss of 2300 m of line. This was replaced with 0.025 m diameter pipeline with socket joints.

(vii) The 0.025 m line has performed well over the first few weeks and has many advantages over the 0.038 m diameter pipeline:

- The flow rate is in the turbulent zone and therefore the pipe should clean itself.
- It is a more 'balanced' system with the static head available at Warsop Colliery for this type of grout and required flow rate.
- It is cheaper to buy and easier to install.
- It is quicker to fill and flush because it does not hold the same volume of liquid.

4. CONCLUSIONS

The main advantages of surface pumped grouting systems are:

(i) The considerable savings in shaft time and underground transport costs.

(ii) The surface grout station provides a healthier environment for the operatives and allows direct filling of the silos with bulk material.

In addition to the filling of the annulus of circular roadways this system could be used for pump-packing, stoppings, void-filling, etc.

When designing a surface grouting system all the relevant factors of the jig-saw puzzle must be taken into account. Some of the more important are:

(i) Grout fluidity and density.
(ii) Static head available.
(iii) Pipeline diameter.
(iv) Pipeline length.
(v) Required flow rate.
(vi) Required pumping pressure.

Attention to the pipeline diameter is perhaps the most critical parameter for the successful operation of such a system and this can be calculated from the minimum working flow rate and the frictional pressure loss.

5. REFERENCES

SHAPIRO, A. H. Shape and Flow.
FOX. Engineering Fluid Mechanics.
MASSEY. Mechanics of Fluids.

6. ACKNOWLEDGEMENTS

The author would like to thank Mr M. T. Hutchinson of Cementation Research Limited and Dr C. A. Pollard of Cementation Mining Limited for their assistance in the preparation of this paper and with the system design at Warsop Colliery.

He would also like to thank Mr L. M. Smith, Director, CML, and Mr J. C. Black, Managing Director, CML, for their permission to present the paper.

Finally, the author places on record that the views expressed in this report are his own and are not necessarily those of Cementation Mining Limited or British Coal.

---

*The author would like to make it clear that the contaminated load of Packset 30 was not supplied directly by Blue Circle Industries.

Erratum

On page 134 of the September 1989 issue of The Mining Engineer, reference was made to the presentation of a crystal decanter to the Institution by the Council and members of the South Staffordshire and South Midlands Branch.

Readers are asked to note that a finely cut lead crystal chalice was presented, not a decanter. Apologies are given for any inconvenience caused.

Surface Grouting of Circular Roadways

By J. MARTIN, BSc (Hons)

DISCUSSION

Paper published in October 1989 issue

C. Outhwaite (Wakefield): Could the author explain why, after a fairly involved theoretical exercise indicating the requirement of a surface pump to prevent problems associated with cavitation and then outlaying the capital on that pump, it wasn't required in practice?

Author: One must realise that during the early stages of establishing the grouting system at Warsop much of the work was unique. At Cementation we had experience of pumping one-shot cementitious mixes which had always required pumping from the surface due to their thicker consistency. Therefore, due to our lack of knowledge of pumping this type of grout we simply purchased a standard pump-packing system from a well known manufacturer and accepted that we may have to modify it to suit our needs. In addition, my theoretical analysis was not complete at the start of the project. I carried out background technical research as time permitted during the initial stages of the grouting works. Fortunately I managed to explain theoretically how the system was performing and equate my calculations to on-site readings. From this point I was able to instigate a number of major improvements, one of which was to commence syphoning from the surface. However, the surface pump was not totally unrequired as it was used to charge the shaft lines at the start of the day and pump a 'ferret' (wiper plug) through at the finish.

S. Brassey (Ayr): I noticed from the author's informative presentation that several quality tests were taken at Shirebrook including test cubes. Did any of these cubes fail the 7 day/28 day designed strengths? Also, what quality tests were taken at Warsop, and how?

Author: A small number of test cube results at Shirebrook did not reach the required 30 MPa at 28 days. Where this did happen steps were taken to improve the mix design strength and the quality control of the whole grouting process. In addition, a number of cores were taken from the sides of the tunnel and crushed. These areas did reach the required strength. Due to the large pulverised fuel ash content, cubes which did not quite reach the specified strength at 28 days were often far in excess after 56 days—in the order of 40 to 50 MPa.

Furthermore, to give a true impression of the grout strength I would suggest that temperature matched cube curing should be carried out. The ambient temperature underground can be 30°C plus, especially when taking into account the heat of hydration of the curing grout.

At Warsop two sets of three cubes were taken every week. By using a relatively high density slurry and a low gelling agent addition rate, I was consistently achieving strengths of between 4.5 and 6.5 MPa at seven days which satisfied our contractual obligations. At the surface, daily checks were made on the slurry densities and batch volumes.

P. Jones (Edinburgh): First of all I would like to congratulate Mr Martin on presenting a very interesting paper. Am I right in saying that the grout arrives in ready mixed batches at Shirebrook? If so, how large are the batches and where are they prepared? If a batch does not satisfy the slump specification, what is the position for getting another batch to the colliery?

Author: The grout arrived ready mixed at Shirebrook in standard concrete wagons each of six cubic metres capacity. The grout was weighed and batched at Tarmac Topmix's Retford plant, approximately 40 minutes' journey from Shirebrook Colliery. If the grout did not satisfy the 100 mm slump specified then Tarmac Topmix had not fulfilled their obligation and our grout plant operative would reject the load. Tarmac Topmix would then supply another load as quickly as possible. Fortunately this only happened on a couple of occasions.

G. O. Morris (Hengoed): Was any compensation claimed from the supplier for the contaminated load of cement?

Is pipeline monitoring used to quickly identify a blockage and prevent the loss of a complete column?

Author: Yes, compensation is presently being claimed from the supplier of the contaminated load of cement.

Yes, we do use pipeline monitoring. If for any reason both tanks are not lowering at the same rate at the surface, then the grout station operative checks immediately with the team at the end of the lines to see if there is a problem. If they have both valves open then there may be a blockage or an air-lock which would be immediately investigated. In addition, we use pressure gauges at a number of points along the lines which provide further information.

A. Shakeshaft (Lowton): After evaluating the design requirements for the system by applying theoretical principles, why were 38 mm pipes accepted rather than the 25 mm pipes required in theory to prevent cavitation? This then would eliminate the need for restrictors in the system.

Secondly, can the author explain in more detail the contaminated load? How can it be ensured that this will not cause further problems in the future?

Author: Cementation accepted the 38 mm diameter pipelines for mainly economic reasons. British Coal had made available these two pipelines to Cementation and if it had rejected them then a claim situation would have occurred in the very early stages of the contract. In addition, the 25 mm diameter pipeline theory was purely academic at the onset and was not being used anywhere to my knowledge. As the works progressed I started carrying out trials with lengths of up to 200 m of 25 mm diameter pipeline in our development headings which proved successful. Then, after the blocked pipeline I had the opportunity to try a full 2300 m length of 25 mm diameter line. The new line worked perfectly and the calculated flow rate of $(1 \times 10^{-3})m^3$/second was borne out in practice and did not require flow restrictors.

We suspect that the contamination may have been caused by using the same wagon for transporting both components. In the morning we had a delivery of Packbent and in the afternoon a delivery of Packset from the same tanker. The Packbent contains the activator for the Packset and unless the tanker was spotlessly cleaned there may have been a small amount left in after the morning delivery. This is what I believe happened. Following this incident we started dealing directly with Blue Circle Industries who operate a Quality Assurance System which involves one of their laboratory technicians inspecting the inside of a tanker before loading. After discussions with Blue Circle drivers I discovered that up to 50 kg of material has to be swept out after each delivery. This would have been sufficient to contaminate the Packset.

C. Finch (Burton-on-Trent): I would like to offer my congratulations to Mr Martin on a very professional presentation. Firstly, could he give details on the advance rates achieved and how close to the face the grouting was carried out?

Secondly, was there any wear on the pipelines?

Finally, what exactly are the flow restrictors and how do they work?

Author: Advance rates of around 45 complete 5.0 m diameter circular rings at 0.61 m centres were achieved working $15 \times 7\frac{1}{4}$ hrs shifts (6 hrs working time at the face/shift). We aimed to grout as close as possible to the face end; this normally meant to within

15 m. The grouting could not realistically be kept any closer to the face without hindering production. Also the inverts were being set behind the Dosco and would have been filled with grout.

We had expected wear to be a problem with the cementitious mix at Shirebrook and therefore thick walled schedule 160 pipes were used. These were also required to withstand the greater pressures. During the two years of grouting at Shirebrook no pipes failed due to wear. At Warsop no pipes failed through wear as expected, due to the much higher fluidity of the grout. However, a number of flexible hoses did wear through, especially if they had been kinked which increased the flow velocity dramatically.

The flow restrictors were lengths of small diameter high pressure hose. Initially I calculated that 30 m of 0.0095 m hose was required at the end of the 0.038 m pipeline to bring the natural flow down to the required 0.001 m^3/s. Small lengths were then added or removed to regulate the natural flow down both lines to the required 0.001 m^3/s. One problem I did have with the flow restrictors was that the extremely high flow velocity (approx 50 km/hr) eroded the hoses. Therefore I designed a reducing funnel from the 0.038 m diameter pipeline to the 0.0095 m hose and starting using extra high pressure quadruple armoured hydraulic hose. Finally, the flow restrictors were laid in a straight line to prevent the possibility of erosion at bends, and all the problems associated with them ceased.