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REMOTE CONCRETE SPRAYING IN SHAFTS AND TUNNELS

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The lining of shafts and tunnels with sprayed concrete is well established. The health hazards associated with spraying in confined areas, as well as the dangers of rockfalls make the remote operation of this process highly desirable. This paper describes an established system for remotely spraying concrete in shafts, which has recently been modified for use in tunnels. The 'Shelob' spraying machine relies on a rapidly rotating disc that flings the concrete onto the shaft or tunnel walls. The process was developed by the Caledonian Mining Company and has been highly successful in spraying linings to shafts in the UK and Africa.

The fundamental requirements of a sprayed concrete lining are considered and then the alternative methods of dry spraying, wet spraying and disc spraying are compared. As well as health and safety considerations, the rate of material application and the efficiency of application are important. The amount of rebound and the quantity required to guarantee the design thickness can be as important as the rate of material emerging from the nozzle. The spinning disc philosophy has many advantages over the traditional nozzle spraying and its robust and simple operation makes remote spraying very practical.

1. WHY SPRAY REMOTELY?

Automating a process can increase the quality and consistency of a product and also reduce costs. Automation also allows personnel to be removed from hazardous and uncomfortable environments. The health and safety implications of automating concrete spraying in shafts and tunnels are substantial. The following hazards are greatly reduced, if not eliminated:

Spray Hazards:	(i)	Dust in the spraying area
	(ii)	Waterborne hazardous chemicals or Aerosols
	(iii)	Rebound materials especially steel fibres
	(iv)	Working with compressed air
	(v)	Noise
Underground Hazards:	(vi)	Rock falls
	(vii)	Fire and Smoke
	(viii)	Water Inrush
	(ix)	Falling down shafts
	(x)	Machinery entrapment

In addition a machine does not necessarily need ventilation or light.

The seriousness of these hazards has been recognised in many countries where legislation severely limits work under unsupported ground. In particular the entry of men into unlined shafts is widely prohibited.

2. INTRODUCTION TO DISC SPRAYING

In 1986, Caledonian Mining addressed the problem of lining shafts for British Coal without man-entry. The system developed involved pumping a cementitous grout onto a spinning disc which propelled the grout onto the walls (Figure 1). By applying a thin coat quickly after boring, the friable strata are sealed and this helps maintain their inherent strength which would deteriorate on exposure to the atmosphere. Polypropylene fibres were added to the mix to reduce cracking and help with building up the layers.

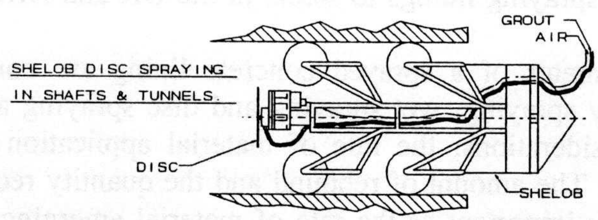

Figure 1.

Since these early days, in excess of 20 shafts have been lined in the UK and Africa with depths ranging up to 220m and diameters between 0.7m and 4.5m. The technique has been developed so that similar material to wet process shotcrete can now be sprayed and steel fibres can be included without difficulty.

The spinning disc is held centrally within a shaft by the use of an eight wheeled support frame as shown in Figure 1. The machine has been called Shelob after the tunnel dwelling spider in Tolkien's 'Lord of the Rings'.

3. DISC SPRAYED CONCRETE

Recent test results have indicated that cores taken from disc sprayed concrete, without fibres, would have a compressive strength approximately 80% of the compressive strength of a cube poured from the same material after 28 days. Figure 2 shows the compressive strength from cubes and from cores at varying ages up to 28 days. It must be appreciated that disc sprayed concrete has only recently been developed and the strength characteristics will almost certainly improve with experience. Results are limited at present so these figures should be taken as indicators only.

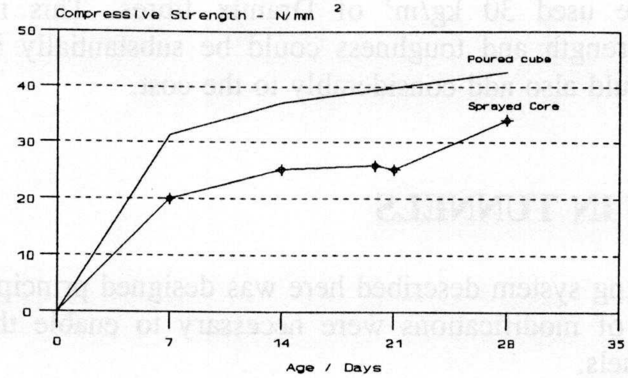

Figure 2.
Compressive Strengths of Disc Sprayed and Poured Wet Mix without Fibres.

Cubes were poured and cores taken from a steel fibre reinforced disc sprayed mix and the results, in Figure 3, indicate a close correlation.

Sample Type	28 Day Compressive Strength
Poured Cube	35.2 N/mm^2
Poured Cube	30.2 N/mm^2
Sprayed Core	23.8 N/mm^2
Sprayed Core	33.1 N/mm^2
Sprayed Core	34.6 N/mm^2

Figure 3.
Compressive Strengths of Cores and Cubes of a Steel Fibre Reinforced Disc Sprayed Mix

Flexural toughness tests on beams of the same fibrous mix have indicated that a poured sample beam will have a similar characteristic to a beam sawn from a disc sprayed sample. Four beams of nominal size 100 x 100 x 350mm were tested in accordance with ASTM1018. Two beams were cast and two were sawn from a disc sprayed sample. The load/deflection curves, indicating flexural toughness, are plotted in Figure 4.

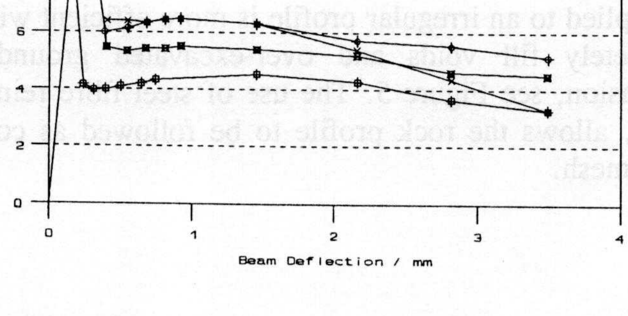

Figure 4.
Flexural Toughness for Steel Fibre Reinforced Disc Sprayed Concrete

The mix described above used 30 kg/m^3 of Dramix fibres. This is a relatively low concentration. Flexural strength and toughness could be substantially improved at higher concentrations but this would also add considerably to the cost.

4. DISC SPRAYING IN TUNNELS

As the original disc spraying system described here was designed principally for spraying in vertical shafts a number of modifications were necessary to enable the disc spraying to function in horizontal tunnels.

Trials of disc spraying on a test rig have indicated that up to 60mm of concrete could be placed with a standard deviation of depth of 10% in a single pass without accelerators. With a suitable accelerator this depth should be unlimited. This compares with an effectively unlimited depth of coat being currently achievable in vertical shafts even without accelerators.

The systems greatest benefit, that of a predictable even coat thickness on a circular circumference, is also a drawback in tunnel spraying where the tunnel floor would receive the same thickness of concrete as the walls. Current development work is concentrating on achieving some degree of directional control so that areas that do not need to be sprayed are avoided (Reference 2).

Movement along a previously prepared tunnel would probably be best achieved by haulage rope pulled at a steady rate. This would be more positive and controllable than driven wheels in a remote operation.

The requirements for a sprayed concrete lining will now be considered with reference to the disc spray process and remote operation.

5. LINING REQUIREMENTS

Any particular shaft or tunnel lining must meet strength, durability, and lifetime requirements as well as being economic. The designer will calculate the depth and strength of concrete to be applied to achieve these requirements. However, to improve the confidence that the applied concrete meets the designed minimum depth characteristics, excess material needs to be sprayed. A higher level of confidence in the spraying process will allow more accurate estimation of required material.

An even thickness coat applied to an irregular profile is more efficient with material and time than spraying to completely fill voids and over-excavated ground to achieve some predetermined final dimension, see Figure 5. The use of steel fibre reinforced shotcrete, as described in Reference 3, allows the rock profile to be followed as compared to ordinary shotcrete reinforced with mesh.

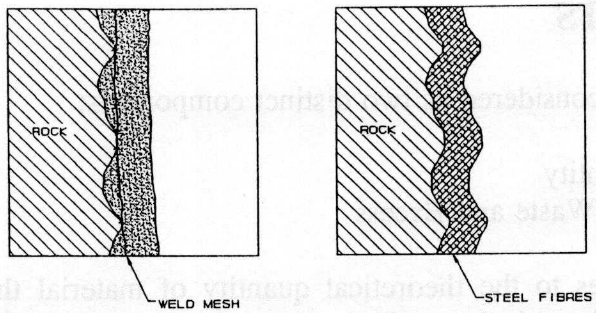

Figure 5
Comparison of Mesh and Steel Fibre Reinforced Sprayed Concrete on an uneven surface.

Confidence in the quality of the applied material is crucial. In hand-held or manipulator assisted dry spraying the quality is very dependent on the skill and consistency of the nozzleman adjusting the water injection. Wet process spraying quality is more dependent on the material pumped. In remote spraying there is no skilled operator at the nozzle and feedback can be difficult. Thus the wet process is more suited to remote operation. Dry spraying has advantages in producing higher strength concrete and dealing with running water.

6. COSTS OF SPRAYING EQUIPMENT

Capital investment is greater for wet spraying, which requires a concrete pump and manipulator arm, than for hand-held dry spraying, which effectively only needs the gun and nozzle. The disc system does not require the manipulator but does require a mounting frame as well as the concrete pump. The high capital expenditure associated with wet spraying is normally only justified where large volumes, in excess of $10m^3$, need to be sprayed in a session and the total spraying for the project is substantial. Disc spraying is most suited to continuous lining of long sections. Capital expenditure would be expected to follow the following pattern:

Capital	Process	Equipment
High	Wet	Nozzle + Manipulator + Dump
	Dry	Nozzle + Manipulator + Gun
	Disc	Disc + Frame + Pump
Low	Dry	Nozzle + Gun

All systems use compressed air although it is more efficiently used in the wet spray process than the dry, and in disc spraying it is used just to drive the disc. In fact, for disc spraying, compressed air could be eliminated if electric motor drive or alternative motor drive were used.

In distant remote spraying, the material and compressed air delivery hoses become a significant capital cost.

7. MATERIAL COSTS

The material costs can be considered as two distinct components:

(a) Design Quantity
(b) Operational Waste and Excess

The first component relates to the theoretical quantity of material that would need to be sprayed if there were no rebound, the profile was cut exactly as per drawing and the spraying process were capable of achieving exactly the design thickness. As these conditions are never met in practice a level of waste and excess material adds to the actual quantity that needs to be sprayed. The operational waste and excess material are subject to three major elements:

(i) Rebound
(ii) Process Capability
(iii) Void Filling

(i) Rebound

Rebound in the dry process tends to be in the region of 20%-30% depending on the skill of the nozzleman and the direction of spraying. In the wet process rebound of 5-10% is typical. For the spinning disc rebound of 5-10% is typical. For the spinning disc rebound rates of less than 5% can readily be achieved. The difference between the wet and dry rebound rates is mainly due to inefficient wetting of the materials in the nozzle in the dry process. The improved performance of the spinning disc over wet nozzle spraying is probably due to the lower intensity of material impacting at a given point. The disc sprays an entire circumference whereas the nozzle creates a point impact with greater disruption. This disruption is reduced by small rotations of the nozzle. Overhead spraying generates greater rebound.

(ii) Process Capability

The process capability refers to the confidence in spraying a set thickness. The combination of operator skill and spray system capability leads to different levels of accuracy in spraying evenly and to a set depth. To ensure the minimum depth is achieved, excess material must be sprayed to allow for variations. This excess material can be thought of as a simple guide to the process capability and is used in the calculation below as the term PC.

The low rebound and even coating capability of disc spraying does allow reasonably accurate calculation of sprayed depth from the quantity of material pumped. In some circumstances, e.g. the internal lining of pipes for corrosion protection, the design depth needs to be achieved as closely as possible since excess depth material could restrict flows.

(iii) Void Filling

Void filling relates to areas that are filled in addition to the design thickness due to the tunnel or shaft profile being irregular, as shown in Figure 5. If voids are filled before the design depth is build up, as in the case of mesh reinforcing, the Filling Ratio, FR, is appropriate. If the spray is allowed to follow the contours, then Following Ration, FR, relates to the actual circumference compared with the design profile.

$$FR = \text{Filling Ratio} = \frac{\text{Design + Void Area}}{\text{Design Area}}$$

$$\text{Following Ratio} = \frac{\text{Actual Circumference}}{\text{Design Circumference}}$$

It can be seen that in all cases the Following Ratio will be greater than the Filling Ratio. Thus, the total quantity of material that needs to be sprayed to achieve the design thickness would be:

$$\text{Material} = \text{Design Qty} \times 1/(1\text{-}R) \times (1 + PC) \times FR$$

where:
R = Rebound
PC = Process Capability
FR = Filling Ratio/Following Ratio

8. ACCELERATORS IN CONCRETE SPRAYING

The addition of accelerators is necessary where high early strength is desired particularly in water bearing strata. A problem with adding accelerators at a nozzle is the lack of time available for efficient mixing and the tendency for plates of over-accelerated concrete to form with softer layers between. The spinning disc designed by Caledonian Mining incorporates a high shear mixer in the head to ensure thorough mixing of accelerator.

9. REMOTE CONCRETE SPRAYING

It has been thought that remote operation of concrete spraying in shafts and tunnels required extensive control and monitoring equipment, as described in Reference 4. Disc spraying allows a different approach to remote operation. By spraying an even coat reliably round an entire profile with negligible rebound, monitoring the applied concrete can be avoided. It is sufficient to check that the spinning disc is performing correctly, that the mix being pumped is the right quality and that the rate of pumping is suitable for the rate of passage along the shaft or tunnel.

Remote spraying experience by Caledonian has identified mix design and hose handling as key issues in achieving reliable, uninterrupted remote spraying.

10. CONCLUSIONS

The key aspects for successful remote spraying of concrete are the ability to provide a stable consistent spraying process and for the lining design to be responsive to the needs of remote operation.

A stable consistent spraying process is more easily achieved using the wet mix processes. The reduced rebound and consistent even lining produced by Disc Spraying coupled with the reliable simplicity of the concept has made remote spraying possible.

In lining design, two positive steps towards remote operation are allowing the use of Steel Fibres for reinforcing and specifying that the lining follows rather than fills irregularities in the tunnel or shaft profile.

Where an even coat needs to be sprayed to a full circumference, disc spraying reduces the amount of material required by its low rebound, even predictable lining thickness and by following profile irregularities.

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