SPRAYED CONCRETE : TUNNEL SUPPORT REQUIREMENTS
AND THE DRY MIX PROCESS

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1. INTRODUCTION

In 1972-73 it was realised that there were likely to be many kilometres of tunnels to be built in the U.K. before the end of the century particularly for long distance water transmission and sewerage disposal and that many of these tunnels would be in rock. It was also noted that there had been little innovation in rock tunnelling practice in the U.K. in recent decades compared with the developments that had taken place in Europe or with the significant improvements that had taken place in soft ground tunnelling in the U.K.

Many of the rock tunnels would be in rather highly-jointed, sedimentary rocks with mixed and changing face conditions and it seemed likely that in the immediate future many tunnels would be excavated by drilling and blasting rather than by tunnelling machines. Thus the shape of the tunnel would be irregular, being controlled to a large extent by the bedding and joint systems rather than by the excavation process. There would be a frequent need to provide immediate support of the ground to prevent falls of loosened rock and to protect the miners from accidents during the erection of the supports.

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The traditional practice is to provide immediate support by means of expensive steel arches, lagging and rock packing where necessary and to complete the whole tunnel. This is followed by the construction of a cast-in-situ concrete lining, often reinforced, and placed by continuous pumping behind collapsible steel shutters. The immediate supports have usually to be left in place and the numerous voids behind the final lining are grouted. Thus the tunnel is provided with two sets of supports which makes construction very expensive compared to the U.K. practice in soft ground. The accident rates are also high because the miners are exposed to rockfalls during erection of the immediate supports.

Significant economies could be made in the support of rock tunnels if only one support system is used. This would need to be placed as excavation proceeded so that it provided any necessary immediate support and it would need to be placed with the miners protected against rockfalls.

The use of prefabricated lining systems, such as precast concrete segments, do not appear to be economic because large quantities of grout and concrete are needed to fill the void between the irregular excavation and the lining. Indeed, cases were known in small sewer tunnels where the volume and the support value of the void filling material was greater than the lining itself.
Support by means of sprayed concrete which has been used extensively in Europe, but very little in the U.K., seemed attractive. It has the advantages of moulding itself directly to the rock, can be placed quickly and remotely with rather simple equipment in layers of different thickness and might serve as both an immediate and permanent support.

A survey of the literature and visits to many tunnels in Europe showed the extent of the use of sprayed concrete. But detailed understanding of its supporting action or of the requisite properties of the deposited concrete were lacking. Indeed it appeared that the properties of the concrete were determined largely by the characteristics of the spraying machine and the method of deposition rather than by the rock supporting needs.

We therefore proceeded with two related experimental programmes of work:

(1) To measure and compare the behaviour of sprayed concrete linings and other support systems at full scale in a special experimental tunnel built in connection with the construction of a major water transmission tunnel for the Kielder Water scheme;

(2) To study the characteristics of existing concrete spraying equipment and the properties of the deposited concrete in laboratory and field trials.
General details of the first year's work in the experimental tunnel have already been published (Ward et al, 1976) and should be studied in relation to this paper.

There are two types of spraying processes in common use for depositing concrete on a surface, wet mix and dry mix. In the wet mix process, pre-mixed wet concrete is conveyed by pump or pneumatic placer along a pipe to a nozzle where compressed air is injected to accelerate and propel the material to the surface. In the dry mix process a dry mix of concrete is pneumatically conveyed at high velocity to the nozzle, where water is injected. The dry mix is the more widely used and the first stage of our experimental work has been restricted to this process.

In this paper we give details of the structural performance of sprayed concrete used to support a tunnel in fissile shale which collapses rather rapidly without any support and we present the general characteristics and limitations of the dry mix spraying system and identify its problems.

2. THE STRUCTURAL REQUIREMENTS OF SPRAYED CONCRETE AS A SUPPORT IN ROCK TUNNELS

(a) Comparative behaviour of different supports in the same rock

Our detailed knowledge of the structural behaviour of sprayed concrete as a support in rock tunnels is limited to our studies
in the Kielder Water Scheme experimental tunnel (Ward et al., 1976). In that project eight different support systems (including no support) are being monitored in the same rock—a highly fissile shale of Carboniferous age. Part of the tunnel (3.3 m diameter at a depth of about 100 m) was excavated by blasting and the other part by a roadheader machine. Four of the support systems used sprayed concrete and it is possible to compare the performance of all systems in the same rock conditions.

This is done in a simple way in Fig 1, which shows the typical downward rock displacements at points 0.3 m above the crown in each support system for a period of about 600 days since

![Fig 1. Rock descent 0.3 m above roof for each support.](image-url)
construction. The left hand diagram shows the results in the part excavated by blasting and the right hand one relates to the machine excavated part. Each of these measurements was commenced in a position 0.3 m behind the face soon after it had been advanced to that position.

The continuing falls of rock from the shoulders followed by the extensive and dramatic collapse of the roof in the unsupported length showed without any doubt the need for support.

The length supported with circular steel ribs at 1.0 m centres, partial lagging and rock packing showed large rock movements in the beginning on account of the loose packing and deformable lagging, but the rate of rock displacement decreased as the packing compressed and the ribs started to provide support. However, slow rock crushing continues behind the supports as small amounts of rock debris fall out between the lagging, allowing displacement to continue slowly, yet quite safely and with the ribs supporting only low loads — less than 1 m of rock overburden. The total roof displacement is now some 29 mm and the loading continues to increase slowly.

In the length supported by rows of seven fully resin-bonded rockbolts spaced at 0.9 m in the roof and shoulders, the roof continued to descend after a while at almost a constant rate and allowed rock crushing to continue. A large shoulder block fell out just before this length was re-supported about a year later by a complete ring of sprayed concrete. The rock bolts
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carried low loads and the new support of sprayed concrete is also quite lightly loaded, because of the large displacements (about 20 mm) that occurred prior to its construction.

Another length was supported with an arch of sprayed concrete placed in two layers each to a minimum thickness of 50 mm, with a layer of light steel mesh between. This allowed smaller movements than the rockbolted length, but again after a while the rock and the arch continued to descend at almost a constant speed, with rock crushing and concrete breaking away along the sides of the tunnel. After a year and some 11 mm of roof displacement it became necessary to re-support this length by completing the invert with sprayed concrete to form a closed ring support. The very instructive behaviour of this support length is presented in detail later.

In two other lengths, one in the blasted part and another in the machine excavated part of the tunnel, the previous arch of sprayed concrete was combined with the earlier array of rockbolts, the rockbolts being inserted after the first layer of shotcrete had been applied. In both these lengths the supports behaved almost identically, only small displacements (3-4 mm) of the roof rock being recorded. However, displacements continue very slowly and the supports are not entirely satisfactory. In all three arches of sprayed concrete, with or without rockbolts, the early circumferential strains in the sprayed concrete were large and remained fairly high in the roof, but along the sides the concrete became hollow (detached
from the rock in places within a few days of placement. In the arch of sprayed concrete without bolts this was followed rather soon by extensive breaking away of the concrete and crushing of the rock behind. Just recently a similar failure has developed rapidly in a local area away from the instrumented part of the sprayed concrete with rockbolts length in the machine cut part of the tunnel. The reason for the localised rock crushing along the sides of the tunnel has been demonstrated by means of a simple model of the orientations and positions of the existing discontinuities in the rock mass in relation to the orientation and size of the tunnel (Ward, 1977).

The circular steel liner length, consisting of butt-welded 12.7 mm plate fitted tightly to the rock with a weak grout, and the length consisting of a complete ring of sprayed concrete, both in the machine excavated part of the tunnel, have performed in a similar way and are entirely satisfactory to date. The rock movements have been quite small, only 1-3 mm. Both of these supports carry quite high loadings equivalent to about 30 per cent of the total overburden of about 100 m of rock, which built up rapidly as the face advanced. During the second year after construction the loadings increased about a further 10 per cent.

It was made abundantly clear from the results of the first year's observations in the experimental tunnel (Ward et al, 1976) that the design requirements for a tunnel support involve a complex interaction between the dilation of the discontinuous
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rock mass and the deformation characteristics of the supports. After a year there was at least a forty-fold variation in the loadings in the different supports, varying inversely with at least a twenty-fold variation of roof rock displacement.

Even at a particular section of one support system with given deformation characteristics the loading at a particular time after construction depends critically on the detailed timing of constructional operations. For example, on how fast or intermittently the face is advanced, where the section happens to be in relation to the face and what time has elapsed since the face was advanced. In other words the loading depends on the timing of the construction operations both before and after the particular section being considered. Many of these critical operational variables are often overlooked and can never be controlled strictly, except by very detailed monitoring measurements. They are among the hazards that need to be allowed for in design and construction and the miner should appreciate them even though he may have incomplete control over them.

Except for rocks which swell by absorbing water into their structure as they are unloaded, the more the surrounding rock is allowed to yield and dilate before the support is inserted, and the more the support yields under loading, the more lightly will the support be loaded and the greater will be the load carried by the rock. These features are well known to the old time miners in many countries, but they are sometimes forgotten today when the emphasis is on speed of construction and attempts
are made, particularly in small tunnels, to place once and for all time hard supports close up to the face. Nevertheless, even in deep tunnels where the deformation at the ground surface can be negligibly small despite large dilation of the rock surrounding the tunnel, too much dilation and too much yielding of the supports is unacceptable. Ultimate stability must be provided in the end.

The yielding limit does not appear to have been defined. It probably needs to be established in terms of the rock dilation, because this substantially augments the rock permeability. In water-bearing ground or around a leaky water tunnel the dilated rock mass becomes a significant conduit surrounding the tunnel. Internal erosion can develop and lead to instability and collapse of supports, unless the rock mass is grouted at considerable cost. How this limiting dilation should be defined remains an open question in the present state of knowledge, but it will be a function of the rock type and the way it disintegrates during dilation.

The deformation characteristics of the support systems used in the experimental tunnel vary considerably.

(1) The supports consisting of steel ribs with lagging and rock packing have a stiffness which increases with rock displacement and is not well defined.

(2) The rockbolts themselves are of constant stiffness, but they can displace bodily with the rock surrounding them, or
when their axial loading gradient exceeds a certain value may allow rock dilation. Failure of the bolts themselves seems very unlikely in our particular rock.

(3) The steel liner is of constant stiffness and is fitted tight to the rock.

(4) A sprayed concrete support has a stiffness and strength which varies with time. Additional layers may be added at different times so that the stiffness and strength of each layer will be different at the same time. Normally an accelerator is added to the concrete to provide high early stiffness and strength, primarily for the purposes of preventing initial slumping and peeling of the concrete from the rock. But this will also attract load to the concrete as the rock dilates. Too rapid a gain in stiffness can lead to circumferential crushing failure of the concrete; equally if the rate of gain of stiffness and strength is too slow in relation to the rate at which the rock releases strain energy it will not support the rock adequately. Clearly sprayed concrete is a versatile support, capable of having its time properties and thickness with time adjusted for optimum economy in relation to the behaviour of the dilating rock.

(b) Detailed behaviour of a sprayed concrete arch, subsequently converted to a ring

We now examine in more detail the long-term behaviour of the
simple arch of sprayed concrete built in the blasted part of the tunnel.

Near the centre of this experimental length in the morning of day - 2 we were approaching the part to be instrumented and the face had been advanced 1 m to position A, see Fig 2. During the day a first array of rock extensometers had been installed, including extensometer No 3, at a position 0.3 m behind the face and the first readings were taken late that day. Early in the morning on day 0 (11 Oct 1974) the face was then advanced 2 m to position B. Three to four hours later the first layer of concrete was sprayed between A and B over the roof and shoulders, and thinned out below axis level. This was covered with a layer of 200 x 200 x 6.4 mm wire mesh. At a position halfway between positions A and B vibrating-wire strain gauges (gauge length 14 cm) numbered 9 to 18 were tied loosely to the mesh and

![Diagram](image-url)

Fig 2. Face & instrument, positions & timing, concrete arch.
orientated circumferentially, see Fig 2. The second layer of sprayed concrete embedded the gauges and was completed 10 hours after advancing to position B. The first readings were taken on the vibrating-wire gauges at this time. On day +1 a second array of rock extensometers, including No 9, were installed 0.3 m behind the face (ie 0.7 m in advance of the vibrating-wire gauges) and their first readings taken later that day. The face was then advanced 2 m to position C in the morning of day 3. It was again advanced 1.9 m to position D near midday on day 4. The sprayed concrete arch in each case was completed within 7 hours of advancing the face.

The advance of the face in metres with time in relation to the position of the vibrating-wire gauges is plotted in the upper left corner of Fig 3 where it is labelled 'face ahead'.

The displacements of the rock 0.3 m above the roof, typified by extensometer No 3 in the first array and No 9 in the second array, are plotted with time across the lower half of Fig 3. Notice the sudden displacement of about 0.5 mm at No 3 as the face is advanced from position A to B and again a sudden displacement of about 1 mm at gauge No 9 when the face is advanced from B to C on day 3. By day 7 when the face had advanced some 10 m ahead the roof displacement at No 9 has almost attained the value at No 3. For the next two years, where Fig 3 has a compressed time scale, the rock displacements both at No 3 and No 9 coincide with each other with differences of only a few tenths of a millimetre. Number 3 is, in fact, typical of all six measurements of rock displacement that were made in the roof of this experimental length.

The circumferential compressive strains in vibrating-wire
gauges 9 to 18 in the concrete are plotted with time in the upper part of Fig 3. Between day 1 and day 3 when the face was stationary at B the strains in the shoulder concrete increased more than in the crown. The slight dip in the plot around the middle of day 1 is associated with drilling the holes for the second extensometer array with rotary percussion drills. When the face was suddenly advanced from position B to C there was an abrupt increase in circumferential strain at all positions.

Fig 3. Face & gauge positions, concrete strains & roof descent with time, concrete arch/ring.
At gauge 9 the response to this effect was noticeably small. The strains continued to increase, though at No 9 there was a fall. Again when the face advanced beyond C there was a noticeable increase in the compressive strains, No 9 again being an exception.

During the week it was noted by tapping the sprayed concrete with a hammer that it had become hollow, ie detached from the rock, in places along the sides up to and somewhat above axis level, but remained tight everywhere in the crown. The strains continued to increase at all points, except at Nos 9 and 10, for some three months. Subsequently during the next nine months all compressive strains decreased, those in the crown only to a limited extent, but quite dramatically on the left shoulder at gauge No 10. In the vicinity of this gauge a crack propagated from lower down the side, where the concrete had been disintegrating. During most of 1975 the rock displacements in the roof had become almost linear with time, and it was clear from our measurements that the sprayed concrete arch was descending as a whole and converging at about axis level.

It was necessary now to decide whether to allow this experiment to continue to a state of collapse or whether to start another experiment which would follow from an attempt to stabilize the support. We took the latter decision and the arch was stabilized after a year by carefully breaking away the loosened portions of sprayed concrete which had not already fallen away.
along the sides, and completing a ring of sprayed concrete by spraying two layers around the invert and sides.

In the new concrete further vibrating-wire gauges were embedded as before and numbered 28 to 43, see Fig 3. Observations on all old and new instruments have now continued for a further year and plotted in Fig 3. Except right in the invert where there are very slight tensile strains, there have been small compressive strains. At gauge 10 where the gauge went into high tension there has evidently been some yielding of the instrument wire, for after the strain was reversed to some extent it was no longer possible to obtain a reading – probably the wire has buckled into compression. On the right hand shoulder of the tunnel where the compression was falling most rapidly before resupporting, eg at gauges 16, 17 and 18, there was the most rapid increase in compression following completion of the ring.

The rock displacements after re-supporting have been exceedingly small, only a few tenths of a millimetre.

A number of vibrating-wire strain gauges orientated longitudinally were inserted in the sprayed concrete and also in panels of sprayed concrete kept in the tunnel. All these show very small strains and it is clear that the strains measured circumferentially in the lining are associated almost entirely with rock loading and not with thermal or moisture movement of the concrete.
It is useful to summarise the magnitudes of the strains and strain rates which occurred at different times in the experiment since these are important design parameters, which need to be quantified if the structural requirements of sprayed concrete as a support are to be specified to suit the rock conditions. Results from other rock conditions would be of considerable value also.

The mean and range of strains recorded in the concrete at different time intervals are summarised below.

**Compressive strains (per cent) in newly sprayed concrete arch**

<table>
<thead>
<tr>
<th>Time interval</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>During first 64 hours when face stationary at B</td>
<td>0.012*</td>
<td>0.005 - 0.021</td>
</tr>
<tr>
<td>Instantaneous strain at 64 hours when face advanced from B to C</td>
<td>0.012</td>
<td>0.002± - 0.020</td>
</tr>
<tr>
<td>During 64 to 91 hours when face stationary at C</td>
<td>0.005</td>
<td>0.002± - 0.008</td>
</tr>
<tr>
<td>Instantaneous strain at 91 hours when face advanced from C to D</td>
<td>0.005</td>
<td>0.001± - 0.009</td>
</tr>
<tr>
<td>Culmulative strain in first week</td>
<td>0.048</td>
<td>0.022 - 0.063</td>
</tr>
<tr>
<td>Culmulative strain in first month</td>
<td>0.064</td>
<td>0.021 - 0.085</td>
</tr>
</tbody>
</table>

* The strain gauges are likely to underestimate the actual strain in the very early life of the concrete on account of their stiffness.

+ The lower values are associated with gauges on the left side where the concrete later fails in tension.
The initial instantaneous strain associated with the first advance of the face may occur at any time in the early life of the sprayed concrete depending on the timing of the contractor's operations. Our instrumentation was partly responsible for the delay of 64 hours, otherwise the delay would have been only a few hours.

In a small 3 m tunnel the whole periphery of the tunnel can be sprayed in an hour or so to provide a closed ring support. In this case the early stiffness of the concrete is likely to be even more critical than in a large diameter tunnel in similar poor ground.

A 10 m tunnel in weak rock is usually excavated with two or three benches progressing behind each other, the concrete arch being extended towards the invert behind each bench. Thus many days, even some weeks, may pass before the sprayed concrete ring is closed. This construction procedure allows considerable dilation of the rock and much smaller structural demands on the sprayed concrete support than in a small tunnel where the ring is completed close behind the face. Even so with multiple bench working in the poor rock zones of the large Tauern and Arlberg road tunnels the Austrians found it necessary to increase the circumferential compressibility of their sprayed concrete by systematically leaving several longitudinal gaps, around the periphery of the concrete. The steel continued across these gaps, buckled inwards and considerably reduced the hazards of falls of crushed concrete which occurred otherwise.
It is not possible at present to interpret the concrete strain observations in terms of stress, and no information is available on the early strength characteristics of the concrete in the mudstone tunnel. It is intended to measure the load-strain properties in the laboratory by straining newly sprayed concrete equipped with identical strain gauges at the rates measured in the field. The effects of high early strains on the long-term strength of the concrete will also be examined since they may be significant.

3. DRY MIX SPRAYING - LABORATORY TRIALS

(a) Equipment and tests
For the dry-mix process a spraying machine of the widely used rotary chamber type was used, namely a Meynadier model GM 57 with a two speed electric drive and a nominal output of 2 to 6 m$^3$/hour. A rubber hose 50 mm bore and 15 or 20 m long was used for conveying the dry mix to the nozzle and an 8.9 m$^3$/min reciprocating compressor supplied the conveying air. For most of the trials a parallel steel nozzle, with water injected 200 mm from the end, was used. Water was supplied by a 0.7 MN/m$^2$ electric pump. The pressure, temperature and flow rate of the water and conveying air were measured in all trials.

Routine tests included the measurement of rebounded material, the wet and dry density of the deposited concrete and the compressive strength of 75 mm diameter cores cut normal to and in the direction of spraying. In selected trials the tensile strength
and bond strength to the substrate were measured and the composition of both deposit and rebound determined by wet mix analysis.

In addition, surfaces of test panels sawn parallel to the direction of spraying were examined to assess material distribution. Initially test panels 1 m\(^2\) by 160 mm thick, mounted vertically in a large wall, were sprayed for subsequent testing; these were sprayed in four layers of equal thickness at approximately 60 minute intervals and will be referred to as large test panels. For the majority of trials, however, panels measuring 600 mm x 180 mm x 180 mm were sprayed in moulds with mesh tops and bottoms to allow for the escape of air and rebound; these small panels were sprayed to full thickness in one application.

All spraying, unless otherwise stated, was horizontal onto a smooth, vertical concrete surface with the nozzle held 1 m from the surface. No admixtures were used.

These laboratory trials were designed to check the effects of mix and process variables on the deposited concrete and the results would not necessarily be expected to be the same as those obtained under practical site conditions.

(b) Materials

Sprayed concrete mixes can be broadly divided into fine aggregate mixes, with a maximum size of 10 mm, and coarse mixes containing aggregates generally up to 20 mm. Most of the work described
here was carried out with the more widely used fine aggregate mix but a limited number of coarse mixes were also sprayed. The gradings used were intended to follow 'conventionally used' gradings (Kobler, 1966); the gradings are shown in Fig 4 and the total wet mix compositions, as discharged from the nozzle, in Fig 5.

(c) General characteristics of the system

Introduction

Let us make a general statement about what is required of concrete deposited by spraying and then see how far the dry-mix process goes towards meeting these requirements.

Fig 4. Aggregate grading, coarse and fine mixes.
It is assumed the deposited material should be dense, homogeneous and isotropic with properties which can be predicted with sufficient accuracy for economic structural design and which are similar to those of well compacted cast concrete of similar composition. The laboratory trials have shown that a number of characteristics, apparently inherent to the process as it is generally used, are likely to detract from these properties. The more important ones are:
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1. Non-uniform distribution of the mix ingredients discharging from the nozzle, resulting in an inhomogenous deposit.

2. Variations in the total water content of the mix, due to the quantity injected being at the discretion of the nozzleman and to time variations in the solids throughput, due to pulsatory delivery at the machine and to partial choking of the conveying system.

3. Orientation of elongated particles in the deposit normal to the direction of spraying.

4. Material losses due to rebound, resulting in a deposit of unpredictable composition.

These points will now be considered in detail.

Materials distribution in the spray

Non-uniform distribution of the mix at discharge from the nozzle is apparent in at least four distinct ways. The cyclic nature of the discharge of the dry mix from each rotor chamber into the conveying pipe results in 'packages' of material moving through the pipe and nozzle; since the water is injected at a constant rate close to the discharge the resulting spray and hence deposit tends to consist of alternating quantities of mix with varying water content, Fig 7(A). The effect on the deposit is shown in Fig 6 (top); here the mix was sprayed vertically downwards with the nozzle stationary and a section sawn through the
Fig 6. Sections sprayed vertically downwards, nozzle stationary (upper), with three traverses of nozzle (lower).

Fig 7. Distribution of materials in the pipeline and on discharge.
resulting cone shows a number of layers consisting of alternate dense and porous bands. Each layer corresponds to a discharge from one chamber of the machine rotor. The pulses of material can be seen frequently during spraying and appear more pronounced the larger the largest aggregate in the mix; even when the pulses cannot be seen their presence can be detected aurally by directing the spray against a suitable surface such as thin plywood or taut polythene sheet. The severity of pulsing is likely to depend on a number of factors, especially the geometry of the rotor chambers and their frequency of discharge. The smaller the package size (ie chamber volume) and the faster the frequency of discharge, then the less severe the pulsing is likely to be. The spraying machine was driven so that the rotor chambers discharged at frequencies of either 65 per minute or 97 per minute, ie one discharge every 0.92 or 0.62 seconds. Examination of the spray at the nozzle by high speed cine-photography showed the average coarse particle velocity to be around 25 m/sec so that at the highest rotor speed the 'pitch' of the pulses would be approximately 15 m at the nozzle although the pitch would be less closer to the spraying machine. Each pulse contains 1.3 litres of dry mix (the capacity of each chamber) or about 2 kg. The pulses do not, of course, consist of discrete packages of material with large gaps between them; discharges from each chamber takes a finite time and the particles travel at different velocities along the pipe. There is also some evidence to suggest reduced pulsing severity the longer the conveying pipe, so some intermingling of the packages of material takes place and the distribution is probably like a series of overlapping skewed distribution curves.
A feature of the spray only apparent from the examination of cine film shot at high speed and described in more detail later is the irregular solids flow in the short term ie in hundredths of a second. Apart from the longer term (around 1 second) cyclic variations due to the chambers discharging and described above, the discharge consists of alternating and irregular clusters of dense solids and sparse, virtually solid free regions. The resolution was not good enough to see the finest particles nor the distribution of the water in the spray.

Another form of non-uniform material distribution is transverse segregation of materials on discharge from the nozzle. This is not always visually apparent and may be due to a combination of expansion of the conveying air and inadequate mixing of the water and finer particles, so that these are carried towards the edge of the spray cone, Fig 7(B). As the nozzle is traversed across the work this effect again gives rise to layers of different density and composition. Fig 6 (bottom) shows a section through a windrow of material sprayed vertically downwards with three traverses of the nozzle ie in three layers, and three fairly distinct layers can be seen.

A fourth source of poor distribution is eccentric discharge, in which most of the solids appear to be confined to one side of the spray, Fig 7(C). This can be seen frequently and is illustrated in Fig 8. The reasons for this are not clear; it may be due to turbulence or some eccentric mixing effect at the water ring or due to the presence of a bend in the pipe close to the nozzle.
Fig 8. Eccentric material discharge.

creating a sidewall effect. If the latter is the case then the effect lasts over considerable distances from the bend - the effect is still apparent with as much as 5 m of hose laid straight between the nozzle and the first bend. Also the stream of greater material concentration has been observed to suddenly change its position without changing the hose position and is not always associated with the region of the nozzle periphery associated with the outside of the nearest bend, as would be expected. The effect of this phenomenon is to produce transverse variations across the spray which can result in concrete of varying composition; it was observed during the spraying of the two specimens shown in Fig 6. The right hand side of both specimens appears weak and porous and may be due to insufficient water resulting in bulking and a region of non-plastic mix.
The combined effect of all these distribution problems is the layered product shown in Fig 9(upper). The layering can be clearly seen and is surprisingly regular considering that the nozzle was moved in a fairly random way during the spraying of the panel. The density and composition through the depth of such a panel have not yet been checked in detail. The layering, although probably always present to a greater or lesser extent in dry-mix sprayed concrete, is not always apparent from broken pieces or even cores and a fairly large carefully sawn surface is necessary to reveal its presence clearly. In extreme cases, however, the layers can be seen in cores and the fracture planes in compression tests have been observed to lie along the layers when these are oriented towards the direction of loading.

Fig 9. Sections through 160 mm thick panels, short nozzle (upper), long nozzle (lower).
All the tests so far described were carried out with a parallel steel nozzle with the water injected 200 mm before the point of discharge; this will be referred to as the short nozzle.

The poor distribution of the solids as they arrive at the nozzle is inherent in the machine design. It is evidently not much influenced by the injection of water largely because of the very short time available for any mixing of the solids and water to occur before the stream disperses out of the nozzle. At a mean particle speed of about 25 m/sec, this being the order of speed determined by high-speed photography, the mixing time in the short nozzle is 0.008 sec. This is an incredibly short time for mixing and it is clear much of the wetting of the solids occurs beyond the nozzle.

The effect of increasing the mixing time by injecting the water into the materials stream 5 m back from the nozzle tip (this will be referred to as the long nozzle) led to a remarkable improvement. With the mixing time in the nozzle increased 25-fold to 0.2 sec the mixing of water and solids was considerably improved and a large number of comparative tests showed that, whereas with the short nozzle layering was always present and became more pronounced with increasing water content, use of the long nozzle resulted consistently in a substantially uniform deposit with very little evidence of layering. Compare the sectioned panel shown in Fig 9 (upper), produced with the same mix and spraying conditions but with the long nozzle, Fig 9 (lower). The effects of the position of the water injection on
on the appearance of the spray can be seen in Fig 10 (upper) — discharge from short nozzle — and Fig 10 (lower) — discharge from long nozzle. The mechanism of water dispersion into a fast moving stream of dry mix has not been examined in detail and is an area which should be investigated further. The advantages of increasing the mixing time by the use of the long nozzle have been empirically established, however, and it is recommended the method should always be used for dry-mix spraying. There are no apparent practical disadvantages to the use of the long nozzle, such as blocking or plugging and in fact there are several advantages from the nozzleman's viewpoint, especially if combined with metered water control (see section of Field Trials). It is not suggested 5 m is the optimum nozzle length. Injection

Fig 10. Discharge from short nozzle (upper) & long nozzle(lower).
of the water up to 10 m back from the hose end has been tried
but without any apparent improvement in the mixing efficiency and
placing the water ring less than 5 m from the hose end has a
practical disadvantage because the nozzleman has to carry its
weight. A higher air pressure is required at the spraying
machine the longer the nozzle. A pressure about 13 per cent
higher is required with a 5 m nozzle compared to the short
nozzle and a limited amount of data suggests this may increase
to as much as 60 per cent higher with a 10 m nozzle.

Variations in water : solids ratio
Two major causes of variations in the total water content of the
mix, ie the ratio of water to solids, are variations in the solids
throughput due to partial choking of the conveying system and
variations in the amount of water injected imposed by the nozzle-
man.

Causes of irregular time changes in the solids throughput can be
attributed to the moisture content of the 'dry' mix, machine des-
ign and operation, and pipeline layout. Sand moisture contents of
4 to 8 per cent are frequently quoted as being the optimum for the
dry-mix spraying on the grounds that moisture contents lower than
this lead to poor mixing and large amounts of airborne dust at the
point of spraying, whilst higher moisture contents cause adhesion
of the fines in the pipeline and ultimately blockages. Experience
with both the long and short nozzle in the tunnel lining trials
described later suggest better mixing and reduced dusting when
the long nozzle is used so that specifying a minimum moisture con-
tent is probably not necessary. The sand used for these site
trials varied in moisture content between 3 per cent and 6 per cent.
with a mean of 4 per cent, below the maximum usually recommended for dry mix spraying, yet sufficient fines adhered in the outlet from the spraying machine to seriously effect the spraying performance of the equipment after about 45 minutes spraying and sometimes within 15 minutes of starting up with a clean machine. The question of the moisture content of the mix needs further investigation and the mix standing time between mixing and conveying also appears to have a significant bearing on the equipment performance; it is suggested, however, that sand for pneumatic conveying with the present machine should be specified as having a moisture content below 4 per cent.

Improvements could be made to the design of the spraying machine to reduce the adhesion of fines in the most critical part of the conveying system, namely the chamber beneath the discharging rotors into which the mix drops at low velocity and the attached taper in which the mix is accelerated into the line, by the main conveying air stream. The use of rubber liners, a more gradual change in the material flow direction, a longer taper or a different arrangement for the air inlet such as multiple or a tangential inlet, might reduce material build-up.

The second source of irregular variations in the water : solids ratio is due to nozzleman who in conventional practice has sole control of the quantity of water injected into the materials stream. The laboratory trials indicate the mix can be deposited with w/c ratios in the range 0.45 to 0.65, that is a variation in the water of about 45 per cent. Such a large variation
SPRAYED CONCRETE

leads to significant variations in both the amount of material loss due to rebound and in the properties of the deposited concrete (see later). The use of a water meter to ensure a steady flow at a predetermined rate would eliminate these variations and also simplify the nozzleman's job.

Particle orientation

A characteristic of sprayed concrete is the tendency for elongated particles to lie with the long axis parallel to the plane of the sprayed surface. This is analogous to dropping a coin on a flat surface - it can only take one orientation. This would give rise to anisotropy if the mix contains a high proportion of elongated material, particularly the larger aggregate.

Rebound

Probably the most obvious undesirable characteristic of sprayed concrete to anyone seeing it for the first time is the large amount of material rebounding from the surface and falling to the floor. This material is scrap and cannot be reused for anything aspiring to be a reasonable quality concrete for a number of reasons. Rebound has been variously reported, (Kobler, 1966, Ryan, 1975, Tynes and McCleese, 1974), as being typically 20 per cent to 50 per cent for overhead spraying, 10 per cent to 36 per cent for horizontal spraying and zero when spraying more than 30° below the horizontal.

Many factors influence the amount of rebound, such as nozzle distance, nozzle orientation, particle size, shape and
velocity, mix grading, cement content, water content, effects of admixtures and the nature of the surface being sprayed.

Particle velocity is of particular interest since this is likely to influence not only the amount of rebound but also the degree of compaction and hence strength and density of the deposit. Particle velocities as high as 150 m/sec have been reported (Lorman, 1968). However, analysis of film taken with a high speed cine camera at speeds of 2,500 to 4000 frames per second have shown that particles when discharging from the nozzle have mean velocities ranging from 15 m/sec to 35 m/sec, depending on the air pressure at the machine, with occasional particles travelling as slowly as 10 m/sec and as fast as 56 m/sec. Particle velocity increases with reducing particle size so that 20 mm stones are generally up to 20 per cent slower than the smallest sand particles resolvable on the film, about 3 mm diameter. A characteristic of the conveying system is the amount of spin imparted to many of the particles; some of the larger, elongated particles have been found to be spinning at up to 250 revolutions per second. These high spin rates could be an important factor in the rebound mechanism.

Another rebound factor is the nature of the surface onto which the concrete is sprayed. It is self-evident that only the finer particles coated with cement will adhere initially when spraying on a hard surface; as this layer increases in thickness a sufficient depth is reached at which progressively larger particles can be embedded, and the proportion of material rebounding
SPRAYED CONCRETE

would be expected to diminish. Most of the rebound measurements in these trials were made by spraying to a depth of 40 to 50 mm over about 1 m² onto smooth, vertical concrete panels and calculating the percentage loss by weighing the total rebound and comparing it either with the weight of the material deposited or the known total material throughput over the duration of the test. 50 mm appears to be about the maximum thickness that can be sprayed horizontally or vertically, even at low water contents, before the material slides or peels; greater thicknesses are likely to be possible with the aid of reinforcement or on uneven surface. This only applies when the deposit is relying on its cohesive strength and before any setting starts.

The measured average rebound for a large number of tests was about 40 per cent for coarse aggregate mixes with a water/cement ratio of 0.4 and 30 per cent for fine aggregate mixes with a water/cement ratio of approximately 0.45. Analyses of the mixes are summarised in Fig 2. It can be seen that the rebound loss increases with particle size so that very roughly 20 per cent of the water and cement are lost, 30 per cent of 0 to 5 mm aggregates, 65 per cent of 5 to 10 mm aggregate and 85 per cent of 10–20 mm aggregate.

At increasing water contents the rebound loss is smaller. Fig 11 shows the relation between water content and rebound (fine aggregate mixes only) within the practical range of water
contents ie w/c ratio from 0.45 to 0.65. The relationship is almost linear with no significant difference between mixes sprayed with the long and short nozzles, varying from 25 to 30 per cent at a w/c ratio of 0.45 to about 10 per cent at a w/c ratio of 0.65. There is therefore a considerable benefit in material economy in spraying as wet as possible. The effects on the strength of the deposit will be described later.

Fig 11. Effect of water content on rebound, strength and density.
Properties of the deposited concrete

The compressive and tensile strength and density of 75 mm diameter cores, cured in water, for replicate coarse and fine aggregate large (1 m²) test panels are given in Fig 12. Both compressive strength and density are lower than would be expected of well compacted concrete with similar cement and water contents. The coefficient of variation of compressive strength is high, being generally in the range normally associated with concrete made with a poor degree of control (Neville, 1973). The direct tensile strength was determined by biaxial fluid test (Clayton and Grimer, 1974) and the bond at the interface was found to be similar to the strength within the sprayed concrete, although the failure in the concrete probably occurred at one of the weak, porous layers.

It was not possible to measure the tensile strength normal to

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Coarse Mix</th>
<th>Fine Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean 15 day equivalent cube strength</td>
<td>Mean 15 day tensile strength in direction of spraying only</td>
</tr>
<tr>
<td></td>
<td>In direction of spraying</td>
<td>Normal to direction of spraying</td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>32</td>
<td>15.4</td>
<td>17.1</td>
</tr>
<tr>
<td>33</td>
<td>22.5</td>
<td>23.4</td>
</tr>
<tr>
<td>34</td>
<td>22.5</td>
<td>21.6</td>
</tr>
</tbody>
</table>

Note: n = number of specimens tested
* = test cores not capped

STRENGTH AND DENSITY OF CORES, COARSE AND FINE AGGREGATE SPRAYED CONCRETE - LABORATORY TRIALS

Fig 12. Strength and density of cores, coarse and fine aggregate sprayed concrete - laboratory trials.
the direction of spraying because of the escape of the compressing medium through the specimen ends via the porous layers.

It should be noted there is no significant difference in the transverse and longitudinal compressive strengths even though all the test panels exhibited the type of layering shown in Fig 9. Directional differences might be more apparent in, say, flexural testing, drying shrinkage or moisture movement tests; it is important to establish the effects of layering on the properties of the material but this would require testing on a more extensive and diverse scale than was possible in the trials reported here.

All subsequent spraying tests were carried out with smaller test pieces measuring 600 mm x 180 mm x 180 mm and the fine aggregate mix only in order to accumulate data more rapidly in the face of limited resources and a large number of variables. It was appreciated that the properties of such small specimens would be even less representative than the large test panels of what could be attained in practice on site, and they were intended only to show any significant changes due to changing variables.

A large number of trials were conducted and such factors as nozzle distance, nozzle tip design, position of water injection, water content and air pressure were examined.
It was found that the smaller test panels yielded generally lower compressive strengths than the 1 m\(^2\) panels and also a considerable directional difference; mean strengths were as much as 50 per cent lower at low water contents and in all specimens sprayed with the short nozzle the longitudinal strength was higher than the transverse, on average 35 per cent higher. These differences due to specimen size are attributed in part to the manner in which they were made. The large panels were sprayed to their 160 mm thickness in four equal layers at 45 to 60 minute intervals so that each new layer was deposited on a partially set layer. The small panels, being well supported by the mould, were sprayed to the full 160 mm thickness in one application and it is thought incipient vertical cracks formed in the material due to slight slumping in the mould. At higher water contents, very large lens shaped cracks were clearly visible in sawn sections, and were probably due to poor mixing or partial slumping.

Small panels sprayed with the 5 m nozzle did not show such defects; the appearance of sawn sections showed fairly uniform distribution of the materials with no marked layering or cracking and no directional strength differences.

The advantage of high water content on reduced rebound has been described and the strength and density of concrete sprayed with both long and short nozzles over the range of
water contents used for the rebound tests are shown in Fig 11. The density and strength of material sprayed with the short nozzle both increase with increasing water content up to a W/C ratio of about 0.6, then apparently start to fall. This fall could be due to a chance effect, such as trapped rebound, or the shape of the curve might be indicating perhaps increasing density due to a more plastic mix with increasing water content up to a certain optimum, followed by a reduction due to the normal trend in well designed and compacted concrete to reduced density and strength with increasing water. The material sprayed with the 5 m nozzle, however, shows a steady reduction in strength and density with increasing water as might be expected. The strength, though, is very much higher at all water contents than that of the mix sprayed with the short nozzle. The difference in the results for the two nozzle types may be attributed to differences in the water content of the deposited concrete. The graphs are plotted against the water content as discharged from the nozzle and it is likely better wetting occurs with the long nozzle and therefore less water is lost to the surrounding atmosphere; photographs of the spray tend to support this. Additionally since a higher air pressure is required with the long nozzle the discharge velocity and hence the compaction effort may be greater, resulting in a higher density and strength.

Further wet mix analysis and measurements of particle velocities with the long nozzle are needed before a true comparison can be made of the effects of the nozzle types on the deposited concrete.
Particle velocity has been mentioned and the effects of increasing the air flow and hence particle velocity on the deposit are shown in Fig 13. These tests were carried out at low water contents using the short nozzle. Particle velocity increases in direct proportion to the air pressure at the spraying machine, as does the density and compressive strength of the fine aggregate concrete. The density and strength of the coarse aggregate concrete falls at the higher particle velocities and this may be due to excessive rebound interference especially in the confines of the mould forming the small test panels; material sprayed on an effectively boundless surface might not show such a fall in strength. It is important to remember that not only are the placing conditions changing with increasing spray velocity, ie the degree of compaction,
but also the composition of the mix is changing because of the probability of higher rebound. The relation between spray velocity and rebound has not yet been examined in detail but some indication of the scale of change can be had from two tests with the coarse aggregate mix; in one test at an air pressure of 0.15 MN/m\(^2\) the rebound was approximately 35 per cent and the compressive strength 22 MN/m\(^2\) whereas in a second test at an air pressure of 0.43 MN/m\(^2\) the rebound increased to 60 per cent and the strength to 40 MN/m\(^2\).

A useful area for further research would be to extend the information of the type shown in Fig 13 to a wider range of air pressures and to examine the effects of varying the water content and the position of water injection. Rebound should also be measured. Optimum process conditions could then be established for a given mix.

4. DRY MIX SPRAYING – FIELD TRIALS

(a) Site, materials and equipment

The opportunity to apply some of the results of the laboratory trials arose with the need to provide additional support to two lengths of the Kielder experimental tunnel. These lengths, each approximately 12 m long and 3.3 m diameter, were in the drill and blast length of the mudstone heading and were originally supported during construction one year previously by (a) rock bolts and (b) sprayed concrete. Additional
sprayed concrete 100 to 150 mm thick was required in both lengths to form a complete circular support.

The rock bolt length had blasted in places to a section more square than circular, particularly above the axis. Since it was required to bring the length to an approximately circular profile the application of sprayed concrete up to 1 m thick would be necessary at the shoulders. In the roof the rock bolts were linked with 50 mm x 50 mm x 3.2 mm diameter steel mesh. Loose rock had collected on the mesh with hollows behind; for safety reasons it was decided not to attempt to remove the loose pieces but to spray as much concrete as possible through the mesh before building up to the required thickness.

In the sprayed concrete length the concrete had been applied during the construction of the tunnel (about one year earlier) in the roof and down to within 0.5 m of the floor; the average thickness above axis level was 160 mm, reinforced with mesh, and below axis level thinning down to 25 mm. The sprayed concrete below the axis had broken away in places and become hollow elsewhere, i.e. detached from the rock and it was proposed to break out this old material and spray the bottom half of the length thus completing a full circle of concrete.

The materials used were ordinary Portland cement, a Zone 3 (BS 882) marine sand and 10 mm single-size, crushed limestone coarse aggregate. The mix proportions were:
OPC/aggregate ratio 1:5, sand/coarse aggregate ratio 7:3. This mix was similar to that used originally in the sprayed concrete length except that the marine sand had to be substituted for a crushed sand which was no longer readily available.

It was intended to use a liquid set-accelerating admixture to facilitate spraying in the tunnel and a commercial sodium silicate solution was chosen on the basis of the extensive use of silicates in sprayed concrete in Europe and its relatively low cost compared with proprietary concrete admixtures.

The same equipment used for the laboratory trials was used at the tunnel. The spraying machine was located above ground adjacent to the concrete mixer and aggregate supply in order to centralise as many operations as possible. The mix was conveyed some 150 mm to the nozzle through both steel and rubber pipe of 50 mm bore. The equipment layout is shown in Fig 14. A field telephone was used for communication between the nozzleman and the surface team.

Over a period of nine working days 130 tonnes of mix was sprayed in the tunnel, the actual spraying time being approximately 20 hours i.e. a spraying rate of 6.5 tonnes/hour. The machine was run at low speed to minimise conveying problems over the comparatively long distance.
(b) **Spraying**

The spraying was in two phases. The first phase consisted of filling in the overbreak in the rock bolt length to bring the tunnel to a circular profile, and this consumed 25 per cent of the total material used. The average rebound was 57 per cent. The short nozzle was used with the water controlled by the nozzleman. No admixtures were used and the material was sprayed with an average W/C ratio of approximately 0.40 although the water content did vary considerably as the nozzleman changed the flow rate seeking an optimum.

The second phase consisted of placing the lining proper in a complete circle in the rock bolt section and in the lower
half of the sprayed concrete length with a lap joint to the old concrete at axis level. Two layers of 200 mm mesh were incorporated in the rock bolt section and one layer in the sprayed concrete section. The long nozzle was used for this work with the nozzle tip removed and the water, injected 5 m back, was preset to a constant flow rate over which the nozzleman had no direct control. An admixture was incorporated. The sodium silicate originally proposed proved unsuitable in above-ground trials and a proprietary aluminate based liquid admixture, Sigunite liquid, was brought in and used at short notice. The w/c ratio was increased to 0.53 average and maintained at this level fairly consistently. The average rebound in this phase was 40 per cent. The total volume of placed concrete amounted to about 40 m$^3$.

The first phase spraying was arduous. The varying angles of the rock surfaces made spraying at 90° difficult. The absence of a set-accelerating admixture meant the mix had to be sprayed with a low water content to produce the firmest possible deposit to minimise sloughing; only about 30 mm could be built up so the nozzleman had to keep moving over the whole 10 m of the experimental length to give the material time to set before applying a further layer. Visibility was very poor due to airborne dust and water. All these factors contributed to the very high rebound loss.

In the second phase the advantages of the long nozzle and the accelerating admixture were quickly apparent. With the
water ring moved back 5 m and the steel nozzle tip removed the nozzleman merely held the end of the conveying hose. There also appeared to be less dusting with the long nozzle. In addition the nozzleman's task was eased by remotely controlling the water. It was found that with the equipment running smoothly the water flow could be kept constant for any spraying orientation; small corrections to the remote valve were made by an observer in the tunnel who was in communication with the surface team where the flowmeter was located. Furthermore with the liquid accelerating admixture added to the water the mix could be sprayed much wetter and the deposit could be built up over quite a small area to a considerable thickness without any danger of sloughing.

Under the right conditions the mix was hardening within about 5 minutes of spraying (the assessment of hardening was subjective; when the deposit could not be deformed by prodding with the finger it was deemed 'hard').

Problems were encountered with cement-admixture compatibility. Several different cement batches from the factory nearby were used in the course of the job and each required a different admixture dose. Temperature changes probably also contributed since not only were the weather conditions above ground changing, and hence the temperature of the aggregate and water, but also the cement temperature varied over a wide range; new cement batches arrived at high temperature — one batch was measured at 110°C. Time did not permit proper compatibility testing and the dose was varied in the mixing tanks
on the surface according to visual assessments of the deposit in the tunnel. The admixture-water dilution had to be varied between 1:6 and 1:12 to produce the same hardening rate. Some form of metering device by which the admixture dose could be quickly and accurately changed according to a quick compatibility test would have been an asset.

It is worth noting that the admixture accounted for 40 per cent of the in-place material cost of £26/m³.

The outstanding feature of the conveying or delivery side of the operation was the frequency of line and machine blocking. The reasons for this have already been discussed. Spraying was stopped 47 times in 21 hours because of blocking in the line or, more often, the machine outlet, and cleaning out accounted for 15 per cent of the total project time (see below). No blockages occurred at all in the 5 m nozzle, nor did the water ring show any serious signs of clogging at the end of each day. Under steady conditions the air requirements for conveying were 10 m³/min of free air at a pressure of 0.38 to 0.44 MN/m² on the inlet side of the machine. A ten per cent variation in pressure below or above this range usually resulted in either a blocked line or leaks at the machine rotor seals and an unnecessarily high spray velocity.

One cause of a number of early blockages was a very small difference in the internal diameters at the junction of the steel pipe and rubber hose at the bottom of the adit. Although this
was only a 2 mm step it was sufficient to cause a solid plug of mix in the line after a short time. It was cured by chamfering the step.

The pipe couplings allowed a small degree of axial misalignment in the steel pipes used in the adit which was sufficient to cause a very high wear rate just downstream of the coupling. Two pipe lengths were completely perforated by abrasion, one after only 18 hours use. Most of the steel pipe sections showed similar wear. The rubber hoses in the conveying line showed signs of abrasion but no measurable reduction in wall thickness.

An analysis of the project time directly attributable to the spraying operation is given below.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Approx No. of hours</th>
<th>Approx % of time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Spraying</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>2. Unloading and positioning of consumable materials</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>3. Setting up, changing position in tunnel and other preparations</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>4. Removal of rebound, rock etc</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>5. Reinforcement fixing</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>6. Setting up instrumentation</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>7. Blockages, cleaning line and spraying machine</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>8. Delays in delivery of consumables</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>9. Support equipment breakdowns</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
Allowing for the uniqueness and experimental nature of the project and the comparative inexperience of the team it would be interesting to know if the 25 per cent efficiency is typical in 'real' tunnel spraying. Nothing appears to have been published on this. When rebound loss is taken into account, the useful spraying time drops to 15 per cent, with 10 per cent for 'spraying rebound'.

(c) **Strength of cores**

A month after spraying 42 cores 75 mm diameter were cut, 21 from each tunnel length and a number of these were compression tested at age 3 months. Density was also measured. The results are given in Fig 15. The bulk of the tested cores were from the lining proper, which was sprayed with the long nozzle and incorporated the admixture, rather than from the overbreak infill.

<table>
<thead>
<tr>
<th>Core position</th>
<th>Mean 3 month compressive strength (equivalent c.b.e.)</th>
<th>Density kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>Test beam - in direction of spraying</td>
<td>31.2</td>
<td>8.9</td>
</tr>
<tr>
<td>Test beam - 90° to direction of spraying</td>
<td>30.8</td>
<td>8.4</td>
</tr>
<tr>
<td>Tunnel lining - new concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cores 1, 2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cores 3, 4</td>
<td>31.6</td>
<td>-</td>
</tr>
<tr>
<td>Cores 5, 6</td>
<td>29.6</td>
<td>-</td>
</tr>
<tr>
<td>Cores 7, 8</td>
<td>32.1</td>
<td>-</td>
</tr>
<tr>
<td>Cores 9,10</td>
<td>29.4</td>
<td>-</td>
</tr>
<tr>
<td>Mean of all</td>
<td>30.6</td>
<td>3.9</td>
</tr>
<tr>
<td>Tunnel lining - old concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cores 1, 8</td>
<td>20.6</td>
<td>-</td>
</tr>
<tr>
<td>Cores 9,10</td>
<td>22.5</td>
<td>-</td>
</tr>
<tr>
<td>Mean of all</td>
<td>21.6</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**Fig 15.** Strength and density of cores - field trials.
The composition of the deposited concrete is not known. The composition as sprayed was approximately

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>182 litres/m³</td>
</tr>
<tr>
<td>Cement</td>
<td>345 kg/m³</td>
</tr>
<tr>
<td>Sand</td>
<td>1206 kg/m³</td>
</tr>
<tr>
<td>10 mm aggregate</td>
<td>517 kg/m³</td>
</tr>
<tr>
<td>w/c ratio</td>
<td>0.53, a/c ratio 5.0</td>
</tr>
</tbody>
</table>

At about 40 per cent average rebound, if it is assumed the amount of each ingredient rebounding was approximately as determined in the laboratory test described earlier then the composition of the deposited would be

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>230 litres/m³</td>
</tr>
<tr>
<td>Cement</td>
<td>440 kg/m³</td>
</tr>
<tr>
<td>Sand</td>
<td>1270 kg/m³</td>
</tr>
<tr>
<td>10 mm aggregate</td>
<td>310 kg/m³</td>
</tr>
<tr>
<td>w/c ratio</td>
<td>0.53, a/c ratio 3.6</td>
</tr>
</tbody>
</table>

The magnitude of the strengths and densities shown in Fig 15 are unremarkable at mean values of 30.6 MN/m² and 2272 kg/m³, particularly at the probable cement and water contents given above, although the reduction in strength due to the admixture is not known. What is particularly interesting is the very low variation in these values. With a standard deviation of 3.9 MN/m² (coefficient of variation 12.6 per cent) this could be considered concrete with a high degree of control. Cores cut from the floor were not tested since these were of poor quality and broke into small pieces during coring; this is attributed to the large quantity of rebound trapped. Spraying
vertically downwards presents a problem because of the difficulty of removing the rebound and it may be preferable to gravity place and consolidate by ramming, perhaps using the scoop extensions available with this type of equipment for decelerating the spray - in which case a wetter mix with reduced or no admixture incorporated would probably be necessary.

Small test panels of the type used in the laboratory trials were made during the spraying of the second phase ie with the long nozzle, admixture incorporated and a 0.53 w/c ratio. The strength of cores cut from these panels, although rather more scattered, had a mean value virtually the same as those cut from the lining and also showed an insignificant directional difference. This is somewhat at variance with the earlier laboratory findings at lower water contents and suggests, as previously mentioned, that the minimum test panel size for results representative of spraying on an effectively boundless surface becomes less critical the wetter the mix.

Cores cut from the old lining in the roof of the sprayed concrete section, about 14 months old, had a compressive strength some 30 per cent lower than the newer lining at 3 months, at a mean strength of 21.6 MN/m² although sprayed with a similar machine and mix. A short nozzle was used for the earlier spraying and the water content is not known.
In addition a powder set accelerating admixture, Sigunite, was hand fed into the machine at a high and probably very variable rate.

(d) **Machine operator and nozzleman**

The experience of the machine operator is just as important as that of the nozzleman; he should be able to detect impending blockages or reduced output and performance due to partial clogging in the machine by observing the air pressure at the machine, pulsations in the hose, the volume of material venting from the chamber exhausts and the flow of materials from the hopper, and take fast corrective action to prevent uneven delivery to the nozzle or a total blockage in the pipeline.

Correct operation and maintenance of the spraying machine are of great importance, such as ensuring the rubber rotor seals are not unduly worn and are evenly compressed to prevent loss of air and fines, ensuring the machine hopper is kept full and the mix flows freely into the rotor chambers, and ensuring the walls of the chambers, outlet, taper and chamber exhaust vents are free from any major accumulation of material.

On long pipe runs partial blockages may occur which are self clearing so that spraying can continue, but if these occur persistently or the material flow becomes erratic or markedly reduced for longer than about 10 seconds, the machine should be stopped, stripped, cleaned and checked. At the end of a
shift or for any prolonged stop the machine should be cleaned thoroughly. The importance of all this increases with greater conveying distances. The time lost in locating and clearing a pipe blockage in perhaps poor light and in the confined and congested space in a tunnel can be considerable.

The aim of the men and equipment concerned with the supply and transmission side of the process is to ensure a steady, constant stream of materials to the nozzle so that the nozzleman can concentrate on the placing side of the process without constantly having to correct the water flow to compensate for uneven delivery of solids.

A great deal has been written about the skill required of the nozzleman and how the success or failure of the job depends on his skill. The experience gained from both the laboratory and field trials suggests that one of his major tasks, which has a direct bearing on the quality of the deposit, should be eliminated, that is sole control over the amount of water injected into the mix. It is suggested that the optimum amount of water should be pre-determined by mix design considerations and trial spraying, and that this amount of water only is used. All that is needed to control the water delivered to the nozzle is a simple water flow meter and a flow control valve, which would be located at the spraying machine. This type of control would result in a more uniform, predictable deposit and possibly less material loss due to rebound.
5. CONCLUSIONS

Sprayed concrete acted in the experimental tunnel as a structural arch or ring in circumferential compression.

The concrete was subjected to high early strain rates particularly when placed close to the face soon after it had been advanced to that position and again when the face was advanced soon after the concrete was placed. Depending on the timing of constructional operations a peak instantaneous compressive strain of about 0.02 per cent could occur at any early age, and peak values of 0.06 per cent in the first week and of 0.09 per cent in the first month were measured.

The loading attracted by a concrete arch or ring of given thickness depends critically on the amount of dilation that has occurred in the rock before the concrete is placed, and, where little dilation has been allowed, on the rate at which the concrete stiffens in early age.

For economy combined with early safe support the stiffening/strengthening rates of the concrete need to be optimised in relation to the dilating properties of the rock and the timing and positions of constructional operations.

The versatility of sprayed concrete makes it potentially suitable to meet a wide range of constructional and ground requirements in rock tunnels, but more development and better control is necessary to achieve these objectives.
The limited laboratory and field trials show that there are a number of features in dry-mix spraying, as it is generally used, which increase the variability of the deposited concrete and which are inherent in the system even under good control and placement conditions.

It appears that the simple procedures of increasing the mixing time by means of a long nozzle, and predetermining and presetting the amount of water injected can improve the deposited concrete and reduce the demands on the nozzleman.

The use of an accelerating admixture, correctly dosed and of predictable compatibility with the cement, has considerable practical advantages in allowing the mix to be sprayed at a higher water content for maximum strength and minimum rebound loss.

The effects of admixtures on the long term strength and particularly on the early time-dependent properties required for the optimum performance of a tunnel support system have yet to be investigated but are likely to be of major importance in small tunnels.
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7. REFERENCES


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