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) <u>Materials</u>

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) <u>General characteristics of the system</u>

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.

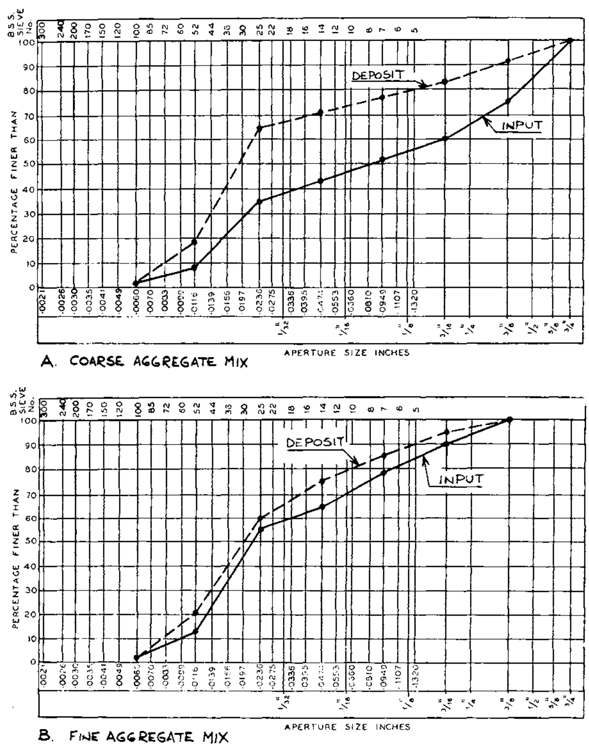

Fig 4. Aggregate grading, coarse and fine mixes.

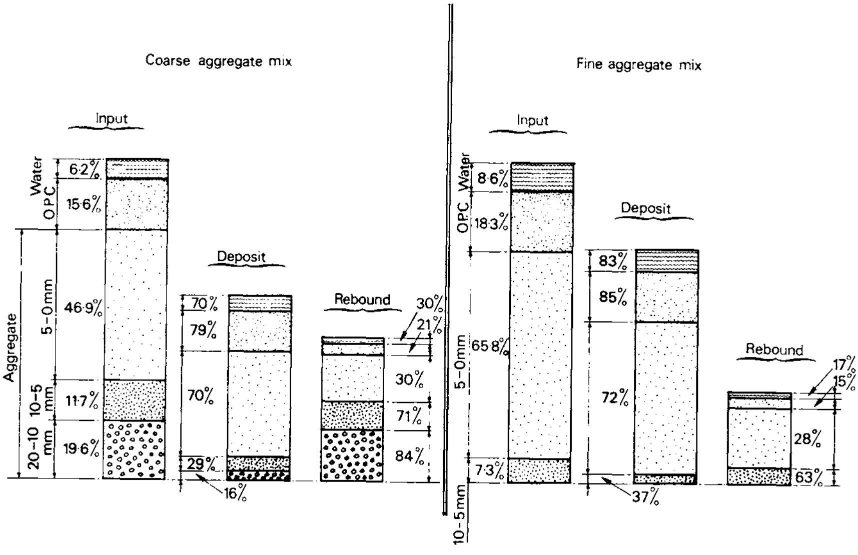

Fig 5. Mix composition - input, deposit & rebound

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:

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

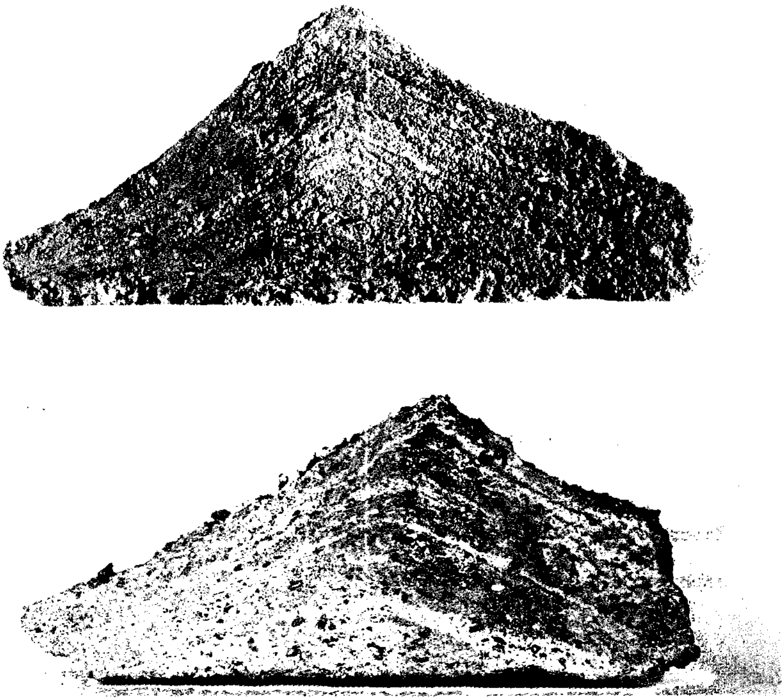

Fig 6. Sections sprayed vertically downwards, nozzle stationary (upper), with three traverses of nozzle (lower).

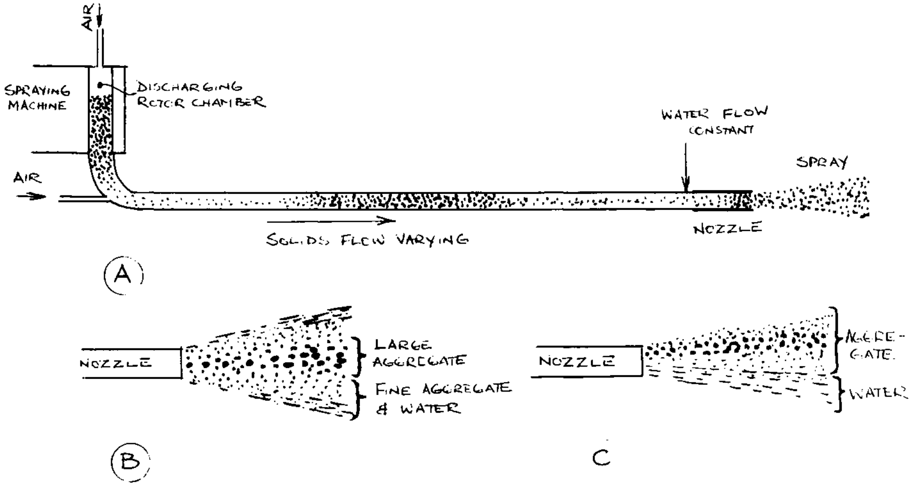

Fig 7. Distribution of materials in the pipeline and on discharge.

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 distribtuion 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

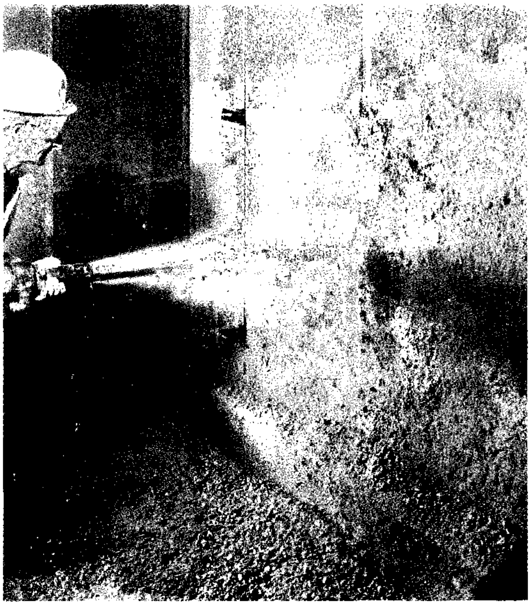

Fig 8. Eccentric material discharge.

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.

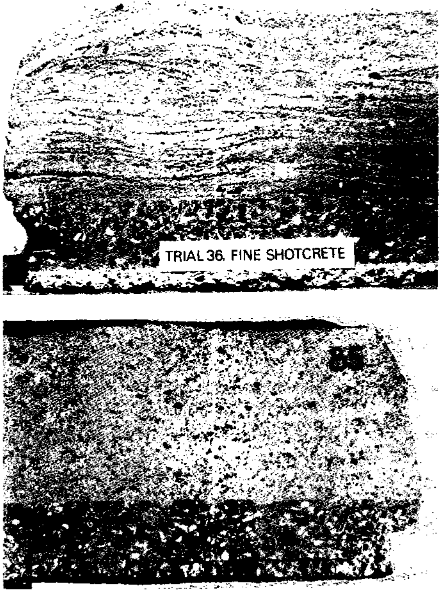

Fig 9. Sections through 160 mm thick panels, short nozzle (upper), long nozzle (lower).