SHOTCRETE FOR GROUND SUPPORT
PAST EXPERIENCE OF EDF

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1 - INTRODUCTION -

Since EDF was founded in 1946, it has achieved a great number of hydroelectric plants, leading it to dig several million cubic meters of underground excavations for the intakes, the power stations and auxiliaries, plus hundreds of kilometers of head race tunnels.

Rather often, these underground structures, standing in poor ground, had to receive a support.

Let us note that since 1950 there have been a few applications of gunite. In fact, it was not exactly a support but rather a rock protection against weathering due to air and water.

We can, therefore, say that, until 1970, the tunnel supports of EDF in bad ground were made almost exclusively from steel arches and laggings. It is of no use for us to go into the inconveniences of this type of structure since it involves difficulty of placement and very high cost price. Consequently, as soon as EDF acknowledged the experiments made in foreign countries, especially in Austria, it began to use shotcrete support. I am now going to try to give you some informations drawn from six years of the application of this process.
2 - LABORATORY TEST RESULTS -

It is not a question here of going into details of the number of tests undergone in the E.D.F. Aix-en-Provence laboratory but to draw some practical conclusions from them.

2.1 - Sampling methods-specimens -

The French Tunneling Society (APTES) suggests using 50 x 50 cm flat boxes at a 45° angle in which 15 cm of shotcrete is projected. Next, cores are cut off from the concrete (Fig. 1).

The tests at the EDF laboratory have shown that the samples taken from it gave exactly the same resistance as those taken from a vertical wall done at the same time.

These tests are generally made on cylindrical cores that are 126 mm high and have a diameter of 63 mm. However you cannot take off these cylinders from concrete which has just been poured. Tests between 0 and 36 hours will therefore be made on cubes with a 10 cm long edge. We should like to point out that for the same concrete the crush resistance is higher on cubes than on cylinders.

2.2 - Types of cements -

Most of the time the cement used in tunnels should resist aggressive water since the shotcrete is much more sensitive to it due to the fact that it is very porous i.e. 20 to 30 % voids. Therefore EDF uses cement containing a large proportion of furnace slag (up to 80 %).

The difficulty with slag cement is to find an efficient accelerating agent. That is why cement makers have created a slag cement receiving an accelerating agent in the course of crushing at the factory. You can also use a quick-setting cement.
Fig. 1
The advantage of these cements is to avoid adding accelerators on site where the dosage is very often inaccurately measured resulting in a waste of a very expensive product. But what is inconvenient is that you must use completely dry aggregates otherwise you have a very short time between mixing and application.

2.3 - Maximum size of aggregates -

Fig. 2 shows that when you use bigger aggregates you don't obtain any appreciable increase in resistance (test having been done on 7, 10, and 16 mm with various types of cement).

Therefore the use of these aggregates doesn't add any advantages but on the contrary produces many disadvantages, among which:

- Increased wear and tear on machinery
- Considerable increase in losses by rebound.

2.4 - Accelerator -

Fig. 3 shows that when the dosage of the accelerator is raised, there is a much higher decrease in resistance which, on the other hand, doesn't diminish in time.

The maximum dosage allowed should be, in percentage of weight of cement:

- 6% for powder accelerators
- 10% for liquid accelerators.
I would not like to make a judgment here on the merits of each process: everyone has his own preferences and has the right to choose whichever one he likes.

I think that the choice of the dry-mix or the wet-mix process can depend on different circumstances according to each specific site.

The following chart sums up the situation:

<table>
<thead>
<tr>
<th>Dry-mix process</th>
<th>Wet-mix process</th>
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<tbody>
<tr>
<td>High velocity projection</td>
<td>Low dust</td>
</tr>
<tr>
<td>better compactness</td>
<td>Low shooting strength</td>
</tr>
<tr>
<td>Facility of use: Dry-mix</td>
<td>Good quality of mixture</td>
</tr>
<tr>
<td>can wait (breakdown or</td>
<td></td>
</tr>
<tr>
<td>incidents on site) ;</td>
<td>Difficulty of use :</td>
</tr>
<tr>
<td>Low cement ratio</td>
<td>Must be used immediately after</td>
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<tr>
<td></td>
<td>adding water</td>
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<td></td>
<td>Little loss by rebounding</td>
</tr>
<tr>
<td></td>
<td>High cement ratio</td>
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As the owner, EDF does not choose the process of application to be used on site but, in the case histories that I will soon show you, our contractors generally chose the dry-mix process. I must point out the fact that the application of shotcrete was on site locations where it was used either on a small scale or was not an everyday procedure. I think that the flexibility in the use of the dry-mix process as well as the possibility of a low cement ratio (300 kg/m³) were determining factors.

Concerning the more recent worksites, we must mention that the dry-mix process has been improved greatly by:

- The placement of a dust collector on the machine (Fig. 4).
- The use of a nozzle with a pre-hydrating ring (Fig. 5) reducing the dust at the time of the projection, therefore giving a more homogenous mixture.
- The placement of a well-studied dosing device (Fig. 6) which allows a regular and economic feeding of liquid accelerator.

Regardless of the improvements and whatever process you choose, we think it suitable to eliminate manual projection because on the one hand it is very painful to hold the nozzle and on the other it is no longer compatible with the total mechanization of tunnel work. This is why we are in the process of studying a new apparatus with a movable arm to apply remote shooting to medium-sized tunnels. This method has already been used in Sweden for larger excavations.

4 - CASE HISTORIES -

4.1 - La Saussaz tunnel -

It is a 7,000 m long pressure tunnel directed to transport a water flow of 85 m³/s. The diameter of the circular excavation is 5.80 m and this tunnel was scheduled to later receive a 25 cm thick lining of shuttered concrete.
Fig. 6
The geological formation is from the Carboniferous period which contains sandstone, schists and formerly exploited anthracite dikes.

In this poor ground, a short experimental tunnel in full section was dug first and you can see in the foreground of picture 7 how it received big steel rib supports and lagging at the crown. The bill of quantities of the two contracts for the whole tunnel took this experiment into account.

Just as we were beginning the digging of La Saussaz tunnel according to the contract specifications, we heard of shotcrete for temporary ground support. In the background of picture 7, you can see now, in the area of the experimental tunnel, the tunnel obtained by shotcrete together with a smooth blasting of the section dug by explosives.

The final shuttered concrete lining of the tunnel was scheduled to be put in place two years later. At our amazement, the shotcrete did not move at all during this lapse of time whereas the steel rib supports became deformed and had to be firmly reinforced.

Picture 8 was taken in another part of the same tunnel. In the center, you can see the metal supports which had been placed at the time we had blasted a small size exploratory tunnel with a 2.20 m diameter. We were able to enlarge this tunnel to a diameter of 5.80 m only with the shotcrete support after a smooth blasting excavation.

Picture 9 shows how the La Saussaz tunnel was given a temporary shotcrete support throughout the majority of its length.
Fig. 8
Fig. 9
In conclusion, I will cite some statistics concerning the downstream section, which is the most characteristic section of the tunnel. Out of the 3,000 m of this section, the bill of quantities took 1,600 m into consideration using steel rib supports and lagging; this length of supported tunnel was evaluated on the basis of (1) the experimental tunnel previously mentioned and (2) from tunnels formerly excavated in similar ground. Thanks to shotcrete we were able to limit the use of metal support to only 80 m.

But this wasn't all: after concrete lining, metal support requires a great quantity of expensive grouting to fill the voids behind the lagging, whereas the use of shotcrete limited this grouting to very small quantities.

In a nutshell, this section of 3,000 m ended with considerable economies in comparison to the cost estimate and this is somewhat rare in a tunnel work.

4.2 - Echaillon underground powerstation -

This excavation is 50 m long, 16 m wide and 28 m maximum high.

The ground was an excellent gneiss and the vault, which was dug first, was pre-blasted so successfully, as you can see on picture 10, that we hoped to leave the rock as it was, without lining it. Unfortunately, after some time, the rock began to split in spite of the low height of the rock above the cavern (i.e. less than 300 m).

We then made a systematic rockbolting with 2 m long mortar-sealed rockbolts placed every 4 m² with a grid spacing of 15 cm. Picture 11 shows the vault completely lined with shotcrete. This shotcrete contained a cement that received an accelerator in the factory.
Fig. 10

Fig. 11
Fig. 12
The vault having been finished we went down to make the excavation always using a smooth blasting process. Picture 12 shows the power station almost completely dug. At the beginning the walls seemed to hold very well. But at the end of a month, the splitting phenomenon similar to that of the vault began to appear. We, therefore, had to perform the same lining. We must note, then, the great advantage of shotcrete. If we had had to make a shuttered concrete lining, the height attained by the excavation would have required a huge and costly scaffolding and the operation would have taken a long time. Due to the shotcrete solution, we were able to work with light scaffoldings suspended to the traveling cranes of the power station and the work was finished quickly.

Needless to say that, here, shotcrete has to be considered as the final lining of the power station.

4.3 - Bramefarine tunnel portal -

We are speaking here of a tunnel portal which includes a rather complicated intake structure.

We had to dig down 20 m long steep slopes in phases of about 3 m high. The ground is composed of very weathered calcareous schists which can be almost entirely split by a pick hammer. Here, the shotcrete on a wire mesh would not resist; consequently a reinforcement was made of 20 m long tension anchor bars placed every 6 m².

Pictures 13, 14 and 15 show a few construction aspects of this temporary support work.

Lastly you must notice that in every above mentioned case we used the dry-mix process and that no complicated calculations were made.
Now I would like to make a few remarks on the use of shotcrete together with tunnel boring machines.

Several years ago, EDF began to use TBMs to bore its tunnels. At present, two TBMs are being used for the hydroelectric plant of ARC-ISERE in the French Alps:

(1) a German TBM, built by WIRTH, with a 5.80 m diameter cutterhead, has now bored more than 7,000 m out of about 11,000 m of tunnel; this machine had previously bored a 4,500 m tunnel on a different site;

(2) an American TBM, built by ROBBINS, with a 8.10 m diameter cutterhead, has now bored more than 2,000 m out of a 4,000 m long tunnel.

5.1 - Efficiency of shotcrete -

First, let us see if shotcrete is efficient in a tunnel bored by a TBM.

In a tunnel dug by explosives, a great deal of the efficiency of shotcrete comes from its ability to fill cracks and holes so that the vault can be rebuilt as evenly as possible. But the walls produced by the TBM are completely smooth and this former quality of shotcrete no longer exists. Moreover, the adherence of shotcrete to the walls is not good and we have examples of flaking after several months of use of a hydroelectric tunnel.

Therefore, it seems to us, that after this experiment, only gunite could be usefully applied for the purpose of protecting the rock from corrosion, but not to support it.
5.2 - Difficulty of immediate projection -

Let us suppose, however, that it is considered valuable to use shotcrete.

The entire TBM installation, including the length of the conveyor belt carrying the muck, extends to 40 m and sometimes more. In our opinion, it is not foreseeable to project shotcrete into all this area because the cumbersomeness does not allow it. Moreover, all the fragile material of the TBM would be quickly covered with shotcrete unless a protection is installed which is almost impossible.

It would be necessary, therefore, to shoot the concrete behind this installation although the application ought to be often made immediately after the digging. But even if the stand-up time of rock is long enough, we could not shoot the concrete without stopping the TBM, whose mucking cars should continue circulating without interruption.

I have just presented the results of our own experience. Perhaps the problem could have been solved elsewhere, but we were not aware of it. (a)

5.3 - A very small scale use of shotcrete -

Very often, in our hydroelectric tunnels, good rock bored with a TBM does not receive a lining. However, the ground can present some faults which are generally full of soft materials so that the circulation of water could enlarge them.

(a) However the Sonnenberg tunnel in Luzern (Switzerland) seems to be an exception. This time the TBM was used as a reaming machine which was pulled from a previously bored smaller tunnel; consequently the rear of the cutterhead was free. The shotcrete as the final lining, was used with rockbolts and wiremesh. (See the British magazine "Tunnels and Tunneling" september-october 1973 issue)
We have, therefore, dealt with these faults in the following manner:

1. Deepest possible cleaning of the faults
2. Shooting of concrete to reconstruct the tunnel walls.

This type of curing (Fig. 16) requires time. However, we have done it on about 3,000 m of tunnel in Liassic schists and the inspections made after several years of the functioning of the tunnel have demonstrated all of its efficiency to be still intact.

6. Aspects of the Contract

6.1. Payment

The cost estimates of E.D.F. contracts usually contain:

- a price of rockbolts (groutable or not)/kg
- a price of wiremesh/kg
- a price of shotcrete/m3

The unit chosen for shotcrete requires a few remarks. We first wanted to pay for shotcrete by square meters; but the walls created by explosives are very irregular and the true quantity of concrete by square meter varied too much. Therefore, it appeared to us that the payment by cubic meters was more fair; we will see afterwards how the quantities are evaluated.

It is indicated that the cost of shotcrete, measured by cubic meter, and actually placed, comprises:

- the accelerating agent
- the losses during placement
- the work of cleaning the rock.
Fig. 16
6.2 - Verification - Measurement -

Certain contract prescribe for a "minimum thickness on peaks of 5 cm". In our opinion, this specification does not mean very much: what is important is the proper filling of faults and holes; in extreme cases, it would not be important if there was no concrete on the rock peaks.

The verification of the quantities is based on two points:

(1) evaluation of quantities actually put in place; we can measure the volume of dry-mix and, by tests on site, deduce the corresponding volume of mortar;

(2) evaluation of losses; we bind an area of tunnel whose invert we cover with a canvas to receive the rebounding materials (which are chiefly coarse aggregates of the mortar).

The verifications can be redone in such a way as to give you evaluations which are as precise as possible.

This system of payment is certainly not perfect. Let us say that it is for the moment the one which seems the least unsatisfactory to us.

6.3 - Price -

The price resulting from tenders varies somewhat. The average fee is established around 650 francs (130 dollars) per cubic meter placed into position under the specific conditions described above. It is a price (taxes excluded) paid by the owner to the contractor.
7 - CONCLUSION -

I would like to conclude a few remarks.

7.1 - The conventional steel rib support can often be replaced by a shotcrete support with or without rockbolts and wiremesh. The latter process is more economical and faster to apply.

However shotcrete cannot be used for all bad ground support problems and it could be very dangerous if it is considered as a panacea.

7.2 - Presently in France, shotcrete is at least two times more expensive than shuttered concrete. Therefore we must try to limit its thickness. In the given examples the average sufficient thickness was from 10 to 15 cm.

Beyond 15 cm shuttered concrete solution will probably be more economical and give you a lining of better quality; we must not forget that shotcrete always has a high percentage of voids.

7.3 - There are still more improvements to be found in the use of shotcrete, such as :

- mechanisation of projection;
- the elimination of dust in the dry-mix process;
- quality and regular dosing of accelerators.

Moreover, loss by rebound should be decreased because a process, which entails a loss of 30 % of an expensive mortar, has no future.