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Towards New Worlds in Tunnelling

Hacia Nuevos Mundos en Túneles

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Shotcreting applied to shell construction in the precutting tunnelling method

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SYNOPSIS: Shotcrete use in the precutting tunnelling method differs from that in conventional temporary-support shotcrete practice. In the former, shotcrete fills a slot instead of covering a surface. However, the two applications share many aspects of interest to shotcrete users. In this paper we will discuss the problems faced and the solutions implemented in optimising the shotcrete placed, in developing the equipment and technique to increase production, and in preparing uniform quality wet shotcrete.

1. PREMILL® TECHNIQUE

1.1 Goals and applications

In the mechanical precutting method a concrete shell is preformed around the tunnel section before the latter is excavated. The shell is made by cutting a slot with a saw-type milling machine that rotates along a mobile frame shaped to the tunnel profile. Cutting starts from the side walls and progresses up to the roof apex. It is usually completed in 5 different stages. Each slot is immediately filled with high-strength fast-hardening shotcrete. Cutting extends below the tunnel's base level so as to guarantee that the foot of the shell is firmly anchored. Each Premill® shell is 3-5 m deep, 15-25 cm thick, and is shaped liked a truncated cone such that it overlaps the previous one (Figs. 1 and 2). In this way an arch is built into the soil, ahead of the tunnel face, to support the surrounding soil mass during tunnel excavation. Mechanical precutting secures its objective of appreciably improving soil behaviour during excavation through a dual-acting mechanism:

- the radial pre-containing action, by avoiding drastic decrease, even temporary, of the minor principal stress σ3, reduces the plasticisation around the excavation since the flow of stresses is channelled along the tunnel boundary through a "medium" with better characteristics than those of the natural soil. In this way an arch effect is developed ahead of the excavation face ensuring the transverse stability of the tunnel;
- the shotcrete shell protrudes about 4 m beyond the face and serves to push the area in which any extrusion phenomena may originate farther forward into the mass of soil, thereby delaying the occurrence of such phenomena and reducing their effects.

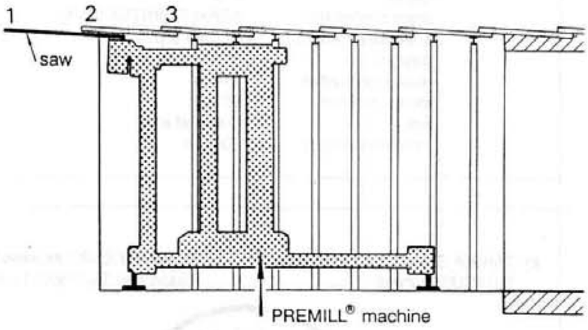


fig. 1 Section of tunnel excavated by PREMILL® technique

1) shell under construction
2) shell without rib
3) shell with ribs

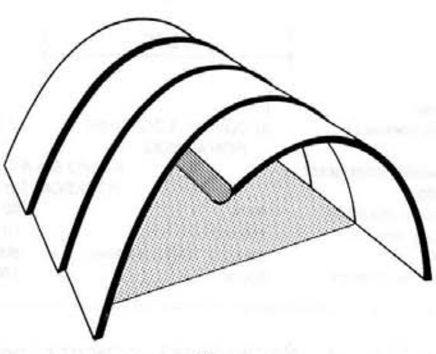
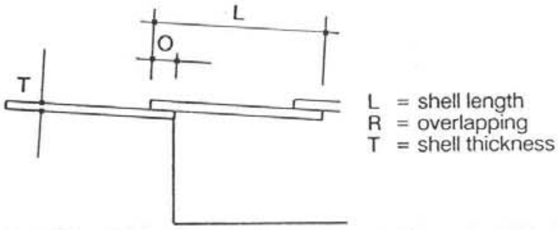


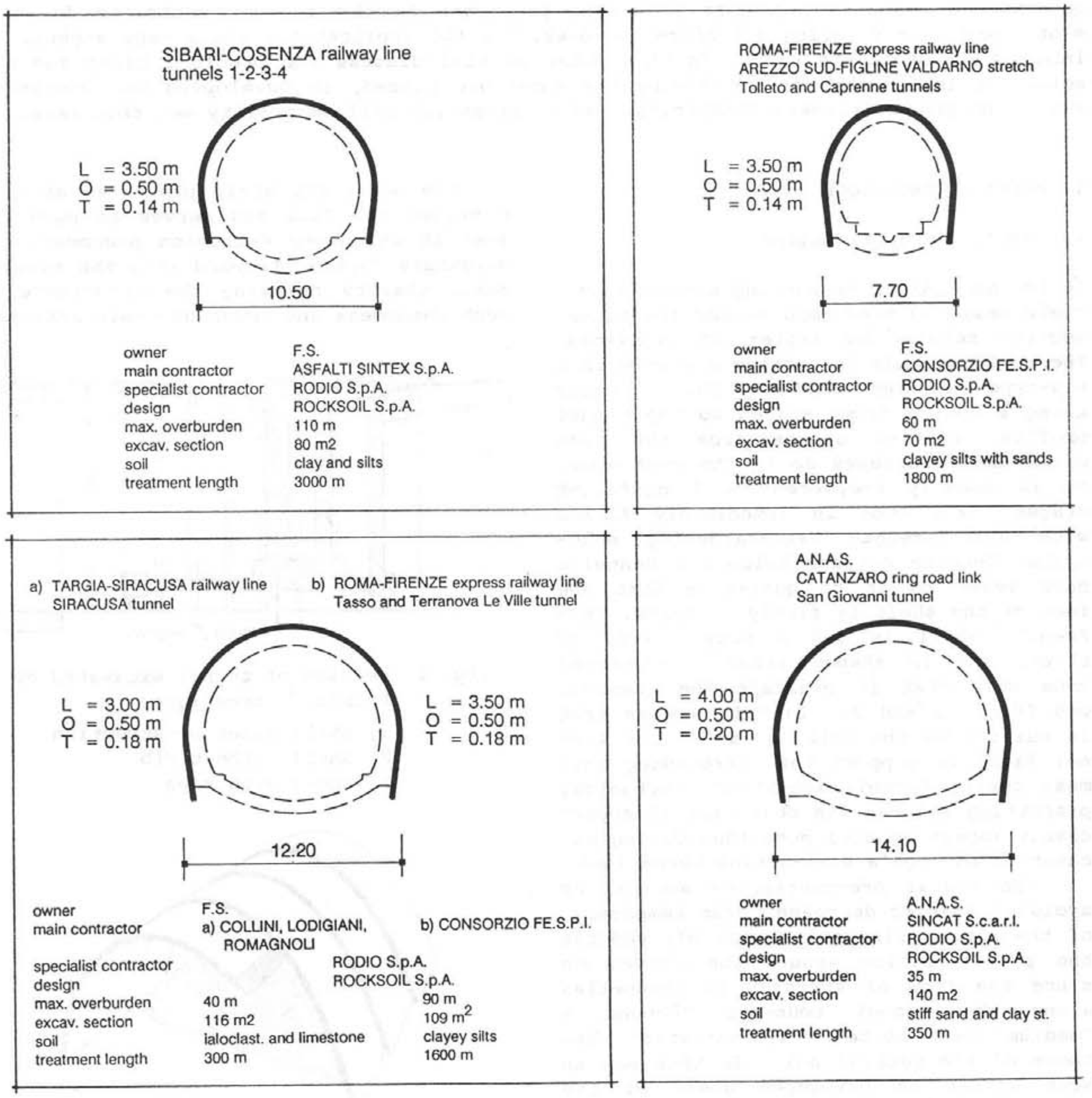
fig. 2 PREMILL® shotcrete shell

Good stability of the excavation face is a vital prerequisite for this method's success. If the Premill® shell by itself cannot guarantee this stability, it must be supplemented by preconsolidating the central core. This may be done by using glass-fibre nails and, where pore pressures are present, by using a ring of drainage holes. (Lunardi 1990).

The precutting technique was applied during the 1970s in France for divided-section profile headings or in small diameter tunnels in rocky lithotypes.

Its main purpose was to prevent the spread of vibrations set up by blasting. It was in Italy, however, that the first application of precutting technique was carried out on full sections (85 m2), in rail tunnels along the Sibari-Cosenza line on cohesive and semi-cohesive soil. The method was subsequently used, again in Italy, on over 6 km of tunnelling and proved successful (Fig. 3).





owner	F.S.
main contractor	ASFALTI SINTEX S.p.A.
specialist contractor	RODIO S.p.A.
design	ROCKSOIL S.p.A.
max. overburden	110 m
excav. section	80 m2
soil	clay and silts
treatment length	3000 m

owner	F.S.
main contractor	CONSORZIO FE.S.P.I.
specialist contractor	RODIO S.p.A.
design	ROCKSOIL S.p.A.
max. overburden	60 m
excav. section	70 m2
soil	clayey silts with sands
treatment length	1800 m

owner	F.S.	
main contractor	a) COLLINI, LODIGIANI, ROMAGNOLI	b) CONSORZIO FE.S.P.I.
specialist contractor	RODIO S.p.A.	
design	ROCKSOIL S.p.A.	
max. overburden	40 m	90 m
excav. section	116 m2	109 m^2
soil	ialoclast. and limestone	clayey silts
treatment length	300 m	1600 m

owner	A.N.A.S.
main contractor	SINCAT S.c.a.r.l.
specialist contractor	RODIO S.p.A.
design	ROCKSOIL S.p.A.
max. overburden	35 m
excav. section	140 m2
soil	stiff sand and clay st.
treatment length	350 m

fig. 3 Mechanical precutting method: applications in Italy (Lunardi 1991)

It has served for advancing full-section headings at a production rate in the order to 3 m/day in tunnels of 70-100 m2 in section. It has shown itself compatible with a work schedule, ensures safety during operations, and has succeeded in soils where other techniques have failed. Continuous checks made during excavations have demonstrated that this method offers appreciable advantages in the way it limits deformation. Accordingly, in the case of shallow tunnels, it is effective in containing surface settlement. The average values noted for convergence were in the order of centimetres and those for surface settlement, in the shallowest stretches, were in the order of millimetres. As such, they were lower than the values that normally characterise traditional excavation methods in similar soils. Other unique features of the method that have been directly verified are (Lunardi 1991):

- the almost complete elimination of overbreaks with a consequently appreciable reduction in the need for contact grouting between the prelining and the soil;
- a reduction in provisional supports, since these are virtually made redundant by the precutting shell;
- intensive mechanisation of work operations and the establishing of regular excavation rates, with benefits both in terms of work-site costs and of the work produced;
- the production of a final lining that can, if required, be reduced in thickness.

1.2 Work sequence

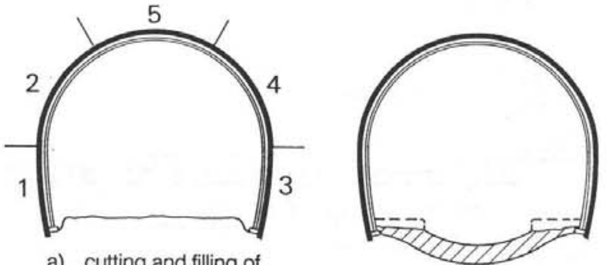
Over a 24-hour period the typical tunnelling cycle can be described as follows (Fig. 4):

1st. step - Premill® shell construction: installation of the machine at the face; cutting and shotcrete filling of deep slots; backing-up the machine from the face to leave room for the excavation equipment;

2nd. step - rib installation underneath the previous arch at 1.5 m approx. from the face: tunnel excavation underneath the last arch and bolting of the exposed face, if necessary;

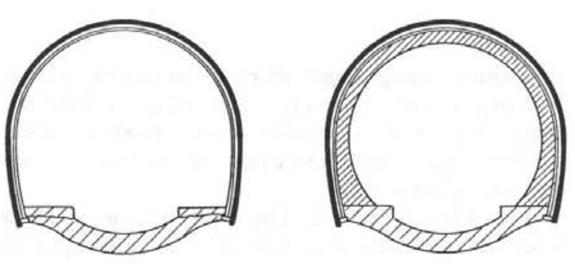
3rd. step - inverted arch excavation and concrete pouring: excavation and casting of the inverted arch must be done so as to leave the space required for the tunnel excavation equipment (approx. 20 m).

Because the method requires at least one excavation operation every 24 hours, respecting the work timetable means that operations begin 6-8 hours after the end of precutting. The shotcrete ageing and hardening time should be the shortest feasible, so that work may go ahead under the Premill® shell in safety, as soon as possible after precutting is completed. It is to be noticed that the Premill® machine, owing to its size, cannot work underneath an arch if its rib has been installed. The arch immediately preceding the face is therefore left without a rib for at least 24 hours.



a) cutting and filling of PREMILL's arch; rib installation; face excavation.

b) inverted arch



c) starter walls pour

d) permanent lining concrete casting

fig. 4 Precutting method phases

2. SHOTCRETE TECHNOLOGY

2.1 Dry shotcrete and wet shotcrete

In the dry shotcrete method, cement, steel fibres, sand and gravel are mixed and pumped dry. The water needed to hydrate the cement is added either at the end, or a few centimeters before the end of the hose. The mix is pushed along the hose by compressed air. In the wet shotcrete technique, the concrete is prepared by adding water to the cement-aggregate mix. Compressed air is then added to the flow of concrete to accelerate it towards the surface of application.

2.2 Dry shotcrete equipment

The mixing and placing plant used in the dry method, as applied to the Premill® te-

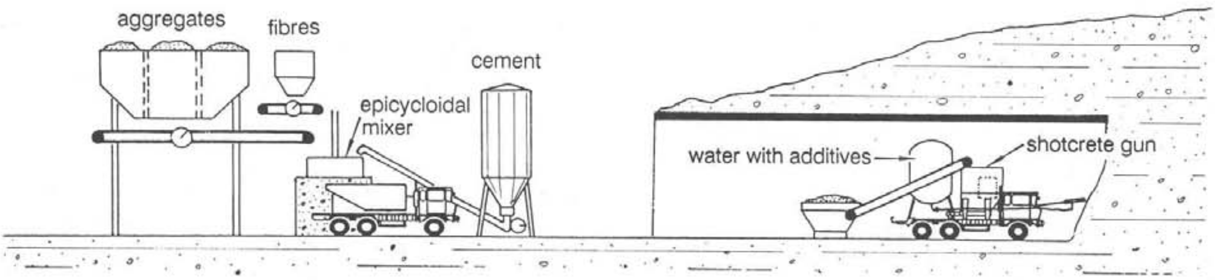


fig. 5 Dry shotcrete plant

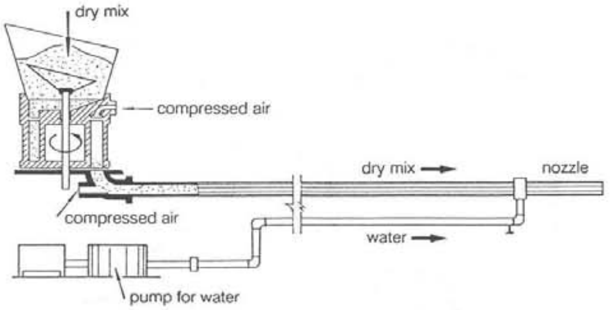


fig. 6 Dry shotcrete equipment

chnique, comprises three separate parts: a mixing plant for the dry mix; a series of dumpers; and a truck that transports the cement gun and carries a stock of water (Figs. 5 and 6).

The mixing plant for the dry mix is stationed outside the tunnel. A conveyor belt is located under the aggregate's container tank and operates in conjunction with cumulative scales in such a way as to obtain the chosen grain-size curve. Steel fibres are added to the aggregate, and this amalgam is fed into an epicycloidal mixer which mixes it in with the cement. The need to avoid segregation and to ensure that the dry mix is as homogeneous as possible render the use of the epicycloidal mixer essential.

The dry mix is unloaded from the mixer into dumpers that ferry it to the face and feed it into a rotary-drum cement gun. In the cement gun the dry mix is emptied out of the mixer into a series of chambers in a rotary drum. From here compressed air drives the mix through hosing, from which it is ejected as a spray. The water to hydrate the cement is added at the point of spray ejection. Water addition is manually regulated and is governed by the amount of dry material arriving at the nozzle, by the moisture content of the sand and gravel, and by the area at which the shotcrete is sprayed. The most sustained mixing action between the cement and water occurs at the moment of impact on the application surface. Accelerators (both for setting and hardening) can be added to the dry mix or dissolved in water and added at the nozzle.

The volume of dry mix unloaded by the cement-gun mixer into the drum's chambers varies according to the load and to the mix's degree of homogeneity. The water flow rate must be regulated by the nozzleman in order to maintain the most constant as possible the water/dry-mix ratio. Accordingly, the operator's judgment is a key factor. However good this may be, his reaction cannot be instant and this inevitably results in a lack of homogeneity in the concrete produced. This is particularly true for the water/cement ratio, and it is this which determines strength. In the Premill®technique, where an arch is built to support the surrounding soil, uniformity of quality in the arch structure is essential. Experienced nozzlemen generally do not have problems in forming a uniform structure. However, only an automatic system can guarantee a uniform quality.

In addition, the dry method entails the following drawbacks: a) the spraying procedure produces a large number of airborne particles; the volume of dust produced when placing 12 to 30 m3 of dry shotcrete has a negative impact on the work environment which cannot be ignored; b) production capacity is low and irregular, with numerous shuttle trips involved and can result in up to 60% wastage; c) when the plant is at a distance from the face or there are operating delays, the moisture content of the aggregate, already mixed with the cement, can precipitate setting - even if only localised.

By contrast, this technique calls for low investment and is easy to carry out.

2.3 From Dry to Wet Shotcrete

In the earliest applications, dry shotcrete was used to cast the prelining arch.

It has served for advancing full-section headings at a production rate in the order to 3 m/day in tunnels of 70-100 m2 in section. It has shown itself compatible with a work schedule, ensures safety during operations, and has succeeded in soils where other techniques have failed. Continuous checks made during excavations have demonstrated that this method offers appreciable advantages in the way it limits deformation. Accordingly, in the case of shallow tunnels, it is effective in containing surface settlement. The average values noted for convergence were in the order of centimetres and those for surface settlement, in the shallowest stretches, were in the order of millimetres. As such, they were lower than the values that normally characterise traditional excavation methods in similar soils. Other unique features of the method that have been directly verified are (Lunardi 1991):

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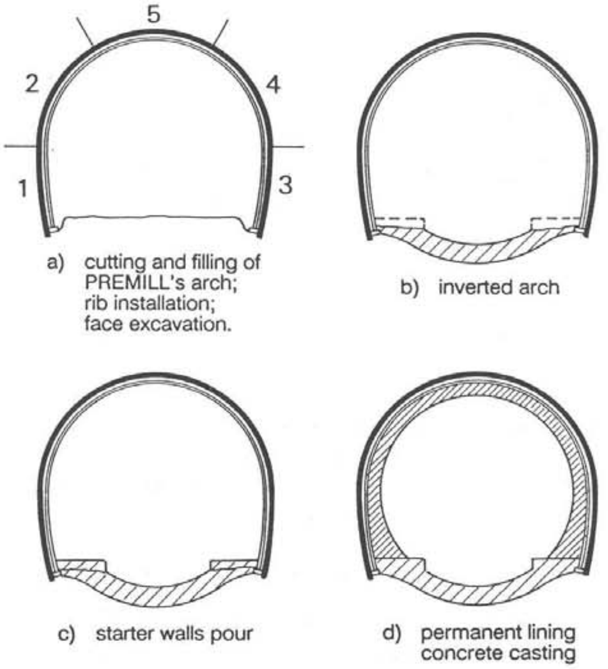

fig. 4 Precutting method phases

2. SHOTCRETE TECHNOLOGY

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2.2 Dry shotcrete equipment

The mixing and placing plant used in the dry method, as applied to the Premill® te-

Dry shotcrete was preferred because the dry mix of cement and aggregate facilitates transport and stocking operations. However, as the Premill® technique developed to larger tunnel sections, a series of problems emerged as the main concern. These related to the work environment, safety of personnel at the work face, production rates, and uniformity of quality. Most safety problems could be solved by mechanising the spraying operation and moving personnel back from the work face area. On the other hand, the type of mix used was the key to improving the work environment and to bettering the shotcrete quality and production rate.

The most obvious solution for reducing dust and increasing production was to use wet shotcrete. In wet shotcreting, as in the dry method, the compressed air added to the dense concrete generates dust. By contrast, though, the particles are wet and therefore less able to stay in suspension. In this way, the generation and diffusion of dust is dramatically reduced, as shown in Fig. 7.

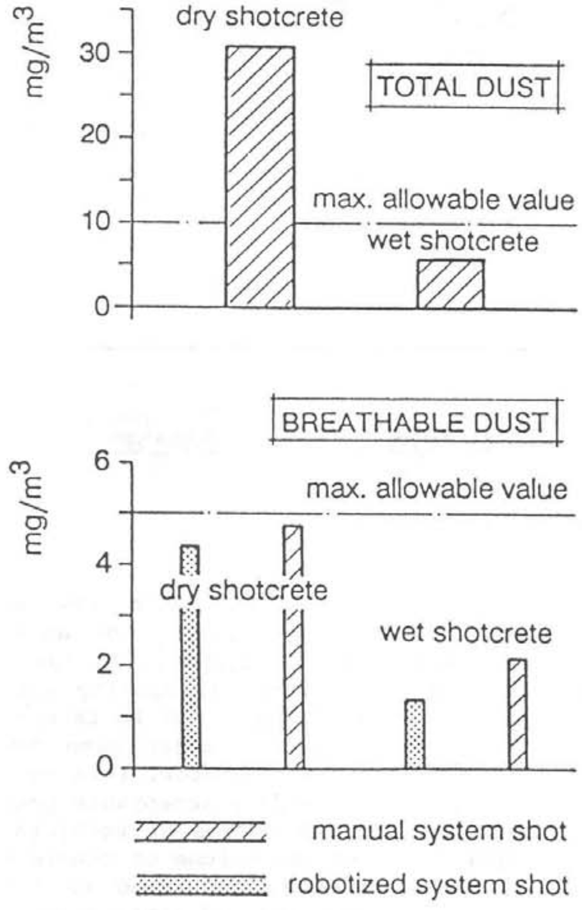

fig. 7 Dust production as a function of shotcrete placing system

The main problem, however, was to develop a mix with high mechanical characteristics and sufficient cohesion to be self-supporting in the open slot being filled. Ordinary wet shotcrete, it may be noted, usually needs a high water/cement ratio for transport reasons and further requires a large volume of setting accelerator (a ratio of 7%-10% to cement by weight) to give the mix sufficient cohesion. Both these factors cause a degeneration in the product's final strength. This reduction in strength runs counter to the Premill® technique because the concrete shell must, in the least possible time, reach sufficient strength to support the soil.

Since with dry shotcrete it is possible to keep a low w/c ratio, efforts were initially made to automate the dry process. A series of on-site experiments showed that it was possible to robotise nozzle movement. However, they also yielded unreliable results when attempts were made to automate the water feed to the irregular flow of dry mix being sprayed.

The conclusion was that, in order to prepare the particular mix needed, a special mobile mixing plant for wet shotcrete had to be developed.

2.4 Wet shotcrete equipment

The composition required for shotcrete - especially the low w/c ratio and the fast-setting cement - ruled out the use of conventional travelling concrete mixers to transport concrete to the tunnel face. This limitation exposed the need to have a high-production mixing system stationed in the tunnel at the work face. The mixing system specification provided for a shotcrete pump powerful enough to deliver concrete with slumps of up to 5 cm and for connection to a proportional doser or accelerator. The goals set in developing such a system were: to improve work environment conditions and safety for personnel working at the face; to qualitatively upgrade the concrete placed and guarantee a degree of uniformity in the quality; to automate the mixing and shotcreting method, as well as to increase production.

Following a series of investigations in the international market for shotcreting equipment, it was decided to build a mobile mixing plant. The need for a high production rate at variable intervals of time related to the Premill®machine's cutting operation gave rise to an unusual set of problems in developing the new plant. The solution was found in the design of a truck-mounted mixing plant with a capacity

A modification was made to the conventional adaptor and a new nozzle design was produced in order to increase the speed of concrete flow. This was necessary so that a depth of 5 meters could be reached with sufficient energy to compact the concrete. A further modification enabled the nozzlemen to turn off the addition of accelerator - a requirement which arose because the use of accelerator was reduced to a minimum during the filling operation.

This method and this pump have been successfully used on three job sites. Judged both from a technical standpoint and for their high productivity, they have given a trouble-free, satisfactory performance. The job sites in question were double-track railway tunnels and the length of tunnel excavated with this method was over 3000 linear metres. The experience has shown that the wet technique described, as applied to the Premill® method, offers the following advantages: high production rates; a more homogeneous cement hydration; suitability for use with mechanised robot systems; and low dust generation. On the other hand, because of the relatively high w/c ratios, the addition of setting accelerators is usually indispensable if there is to be enough cohesion for the shotcrete to adhere to the slot wall.

3. SHOTCRETE DESIGN AND MECHANICAL CHARACTERISTICS

One of the most important factors in the Premill® method is shotcrete behaviour. Because the method requires at least one excavation every 24 hours, the ageing and hardening time should be the shortest feasible. This willallow work to go ahead in safety under the Premill® shell as soon as possible after precutting has been completed. In the absence of particular stability problems, it has been calculated that a minimum compressive strength of 6 MPa is required to safely excavate underneath the arch, and that the maximum time allowed for concrete curing - compatible with excavation rates - is 8 hours. In addition to this requirement, as in all shotcrete applications, slump and right degree of cohesion are important factors. The cohesion enables the shotcrete to adhere to the walls, thereby reducing back-flow and rebound problems. It may be noted that in the case of the Premill® application, rebound material does not go to waste as in traditional shotcrete application. However, since it remains enveloped in the jet of spray it may cause fracture planes within the structure. To sum up, shotcrete must have fast-developing high strength (6-8 hours), the right pumpability, and high cohesion. For it to be successfully applied, it is essential that the correct components and design mix are chosen.

3.1 Components

Aggregate - The choice of type and mix of aggregate for inclusion in the shotcrete must be made when first setting up the work site, since it is governed by the availability of material on site. The gradation curve for aggregates used in shotcreting is suggested by committee ACI 506.2. Three kinds of gradation are proposed (Fig. 11): the finest (ACI-1), for spraying on tunnel roofs or where there are severe rebound problems; the coarser gradation (ACI-3) for spraying on side walls; and the ACI-2 classification for situations between these two extremes. For technical reasons, in Premill® shotcreting practice a single kind of concrete can be applied. Since rebound problems are relatively minor even in the case of tunnel roofs (because spraying is effected in the slot), a gradation midway between ACI-2 and ACI-3 is usually adopted. As with traditional concrete, the better the gravel's sphericity and roundness, the better the pumpability and concrete quality. Moreover, the aggregate's moisture content must be checked in order to determine the right amount of water to be added and the actual w/c obtained.

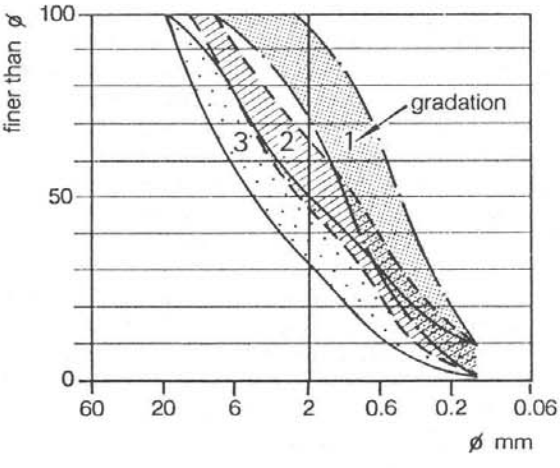

fig. 11 Aggregate grain size as suggested by ACI 506-2 Committee

Cement - High strength cement is employed in dosages between 400 and 500 kg per cubic metre. In applications of this type, unlike in the case of ready-mixed concrete, the ratio of water to cement is not the only important consideration.

Equally significant is the cement dosage per cubic metre of concrete. The greater the former, the more heat generated, and the latter is essential for obtaining high strength in a short period.

Fibres - The characteristics of fibre-reinforced concrete are determined by the type and quantity of the fibres used. The higher the fibre dose and the fibre aspect ratio (ratio of length to height), the better the performance of the concrete. Fibres enhance ductility and impact strength, increase tensile and flexural strength, and inhibit the development of fractures. By contrast, they have no effect on compression strength. Tests on fibre-reinforced concrete have demonstrated that an addition of fibre equivalent to 10% of the weight of the concrete raises tensile strength by 30% and strain at failure by 50%. Fibre has a significant contribution to make because it increases dynamic loading strength. This is crucial, for example, if the concrete is not to be impaired when subjected to jolts from the excavator or to vibrations resulting from blasting operations.

Chemical Additives - During preparation, many additives may be included for a variety of purposes: to accelerate setting or hardening; to increase cohesion and reduce rebound; to reduce the quantity of water; and, in emergencies, to retard setting and improve fluidity.

Accelerating agents divide into those for hardening and those for setting. Their functions are entirely different. Agents that accelerate hardening (i.e. chlorides) serve for increasing strength during short ageing. Those that accelerate setting produce an instant set on the slot surfaces. On the first Premill® job sites, hardening accelerators were added to dry shotcrete to give greater certainty that early strength would develop in the prelining arch. However, experience showed that the minimum required strength of 6 MPa could be reached and exceeded in 8 hours (unconfined compressive strength) by using just fast-hardening cements (Portland 525) with dosages ranging between 400 and 500 Kg/m3 and W/C ratios between 0.5 and 0.7. The function of setting accelerators in the Premill® technique is to reduce the fluidity of the shotcrete once it is in situ. In this way, the shotcrete will adhere to the walls and back flow will be reduced. The accelerators chosen were aluminate based. As compared with silicate accelerators, these may be used with a much lower dosage (2-5%) and they cause less long-time strength loss. Furthermore, the concrete does not set immediately, as occurs with silicates. Instead, there is a delay of a few seconds and this offers advantages: the concrete in situ may be compacted by the succeeding jet of spray, and the lower rigidity reduces rebound. Four different brands of aluminate-based accelerators were tested. The conclusion reached was that at low percentages (with an accelerator/cement ratio by weight of 2%), all accelerators gave the shotcrete the same stability and the same short-time compressive strengths. On the basis of the experience gained we can state that the best way of obtaining self-supporting shotcrete with high mechanical characteristics is to keep the water/cement ratio to a minimum and to add low percentages of aluminate-based accelerators.

In a few applications silica fumes have been used to improve the cohesion of the mix sprayed. The known advantages of adding silica fumes, such as greater cohesion (with rebound reduced from 30% to below 8%) and an increase in shotcrete's long-term strength and durability, were verified. However, it was found that the advantage/cost ratio in our applications was low and that handling the fumes in the tunnel without creating dust posed numerous problems.

3.2 Composition

Composition may vary significantly according to the concrete characteristics necessitated by structural factors, operational requirements, or by the placing technique. Broadly classified, the composition adopted on Premill® sites in Italy (Fig. 4) may be summarised as follows:

dry shotcrete	
high strength cement	400-500 kg/m3
aggregate (ACI 2-3)	1/4 1700 kg/m3
steel fibres	30 kg/m3
water-cement ratio	0.4-0.5
CaCl2	4-6% of cement

wet shotcrete	
high strength cement	400-500 kg/m3
aggregate (ACI 2-3)	1/4 1700 kg/m3
steel fibres	30 kg/m3
water-cement ratio	0.5-0.7
aluminates	2% of cement

3.3 Characteristics

A clear statement of the advantages obtainable with shotcrete is no simple matter owing to the influence of contingent factors. These include the nature of the materials applied, the method of application, and the site. Indeed, the characteristics of very-short-term strength vary widely, since they are highly sensitive to the following factors: cement (fineness and tricalcium silicate content); temperature (of the products used and of curing - and therefore, indirectly, by the geothermal situation and the volume of concrete cast); w/c ratio adopted, which may vary appreciably according to the aggregate used (grain size, roundness, sphericity, and mineral composition); presence of additives; placing (time and method of mixing, degree of compaction, loss of moisture content, and homogeneity).

Accordingly, it is difficult to provide significant data for short ageing. However, a broad guide is given in the graph in Fig. 12 showing the average for a large number of samples. The latter were taken from different sites and produced with the wet shotcrete method and the composition specified above.

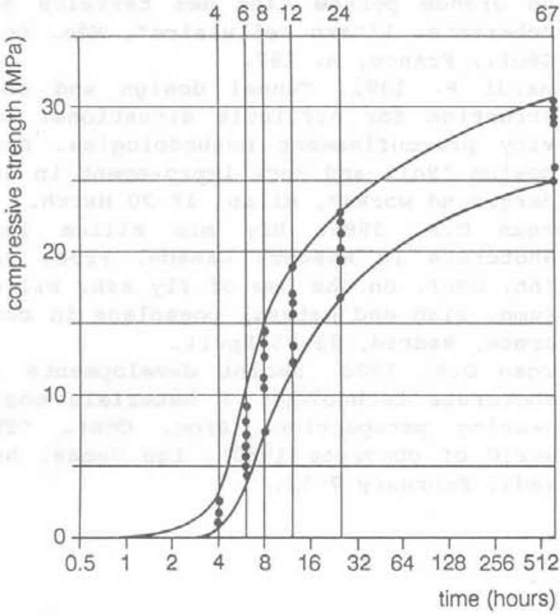

fig. 12 Shotcrete strength evolution versus time

3.4 Checks during operation

From what has been stated above, it is clear that tests on concrete mixed and cured in a laboratory can only offer a rough guide. They serve more for comparing different compositions than for determining the real results that can be obtained with shotcrete. Of far greater significance is on-site sampling, carried out during operations. However, concrete coring can only be performed after fairly lengthy ageing and, in any case, not before the soil underneath the shell has been excavated. For this reason the coring is inappropriate for obtaining samples to test for short-term strength (i.e. 4-12 hours). Accordingly, it is indispensable to take samples of fresh concrete during spraying. In order for such samples to be sufficiently representative, tests must be conducted on different samples and an attempt must be made to reproduce as closely as possible the concrete's in-situ curing conditions. With this aim trials were run to identify the heat conditions and to select the most realistic type of mould and curing conditions. Thermocouples were inserted into the Premill® shell to measure the temperature throughout the curing process and to obtain curves describing in-situ temperature variation. Using the same method, temperature variation was measured in samples which had been cured in differing kinds of moulds (test cubes of expanded polystyrene, plastic, and iron). As may be seen from Fig. 13, the result that most realistically corresponded to on-site conditions was obtained with the samples left to cure in insulation (polystyrene). Even at relatively high temperatures, these samples display appreciably higher strength values than the same samples cured in conditions allowing heat loss (Fig. 14).

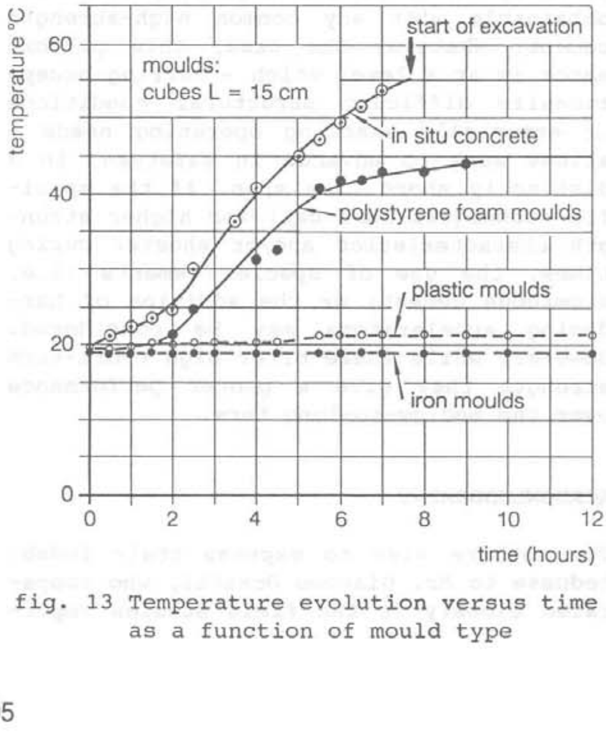

fig. 13 Temperature evolution versus time as a function of mould type

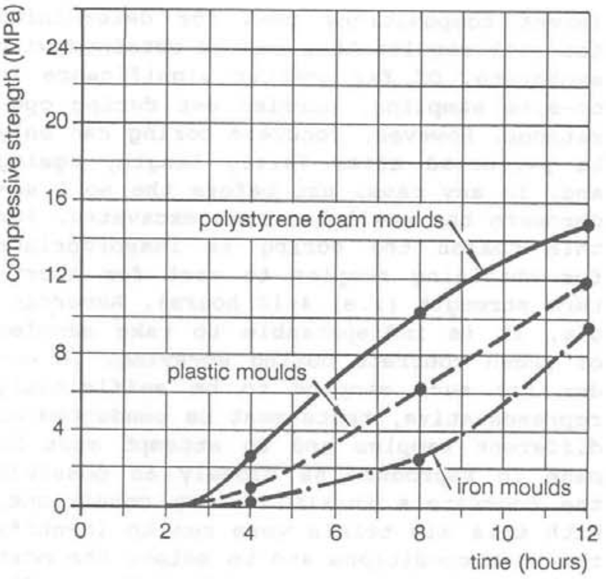

fig. 14 Concrete compressive strength versus time as a function of mould type

4. CONCLUSIONS

The dry shotcrete method is still useful if applied to small-section tunnels (i.e., single-track tunnels) and backed up by systems for robotised spraying and for dust laying. Under these conditions it can meet production demands. By contrast, the wet shotcrete method developed by RODIO becomes a virtual necessity on large-diameter sections or for faces located at a notable distance from the tunnel entrance.

We feel able to claim that with the above-described methods, whether for dry or wet shotcrete, the concrete quality is probably close to the highest performance obtainable with any common high-strength cement. Whatever the case, this performance is at a level which - barring exceptionally difficult structural conditions or especially exacting operating needs - allows work to advance in safetyand in a distinctly short time span. If the specific techniques used call for higher strength characteristics and/or shorter curing times, the use of special cements (i.e. aluminous cement) or the addition of hardening accelerators may be considered. However, while these offer high short-term strength they give a poorer performance over the medium-to-long term.

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