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Construction Chemicals

SPRAYED CONCRETE FOR ROCK SUPPORT

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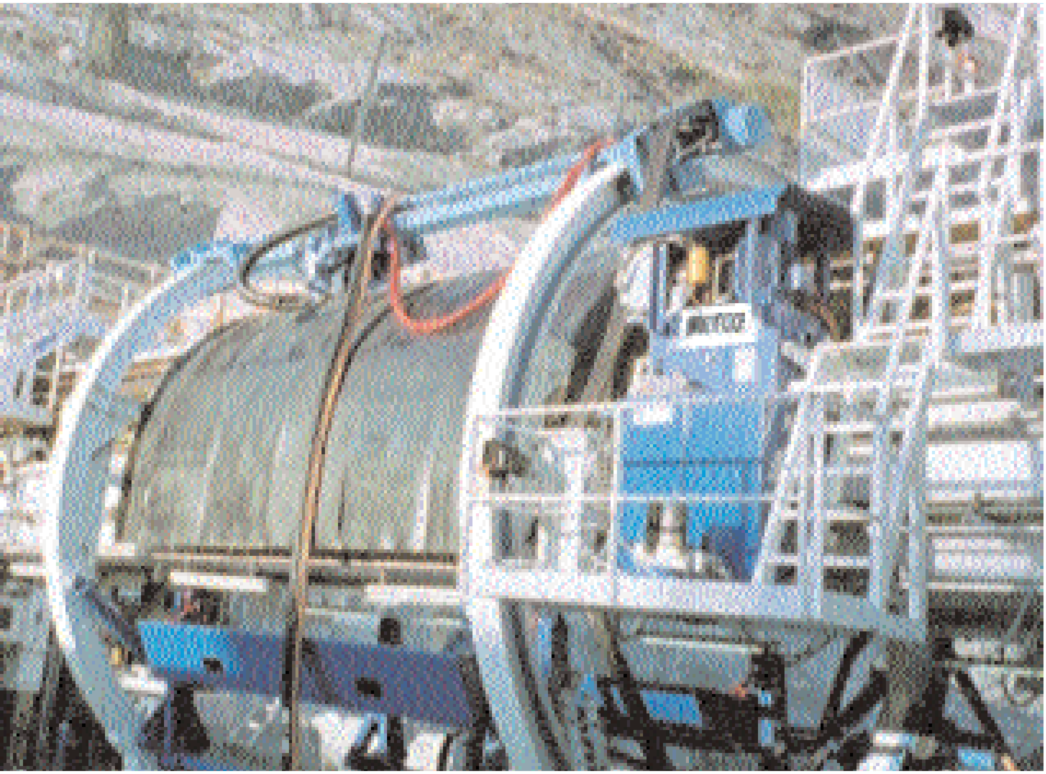

UGC International

Building Tomorrow Together

MEYCO® robotic spraying system mounted on a Herrenknecht TBM in one of the AlpTransit (NEAT) tunnels in Switzerland (Lötschberg Tunnel in Steg).

SPRAYED CONCRETE
FOR
ROCK SUPPORT

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1. Introduction

Human creativity springs from the natural desire of mankind to know and its capability to learn. Explorers and discoverers possess these features in a high degree: They are driven by an unrelenting curiosity to go beyond the boundaries of the known, to explore into the nature of things, to reveal connections between ideas, facts, conceptions, to view things from new angles, to change perceptions.

A well-known fact about the construction industry – and underground construction in particular – is that all projects are unique. The degree of complexity due to the intertwining of the variety of project-related parameters is higher than in many other industries, thus forcing contractors as well as suppliers to be truly adaptable and flexible.

The enormous advantages of sprayed concrete as a construction and rock support process and the improvement of materials, equipment and application know-how have made it a very important and necessary tool for modern underground construction works. The development of modern wet-mix sprayed concrete in particular has enlarged the field of underground construction work. Projects that were impossible to be realised, have now become practicable. Subsurface structures can be placed where they are needed, without regards as to rock and conditions.

1.1 What is sprayed concrete?

Sprayed concrete or Gunite is not a new invention. Sprayed concrete (mortar) has been known for more than eighty years.

The first sprayed concrete jobs were done in the United States by the Cement-Gun Company, Allentown as early as 1907. The first device made for spraying of dry materials for new constructions was invented in Pennsylvania in 1907 by Carl Ethan Akeley, who needed a machine to spray onto mesh to build dinosaurs. His company, the Cement-Gun Company, protected the brand name «Gunite» for their sprayed mortar. This mortar contained fine aggregates and a rather high percentage of cement.

The name Gunite is still used. In some classifications Gunite stands for sprayed mortar, but the grain size limits are not consistent: Depending on the country, the limit for the maximum aggregate is defined as 4 mm, 5 mm or even 8 mm. To avoid this confusion between sprayed mortar and sprayed concrete, we prefer to use the expression «Sprayed concrete» for every sprayed mixture of cement and aggregates.

Today there are two application methods for sprayed concrete: The dry-mix and the wet-mix procedure. There was only dry-mix sprayed concrete in the beginning. In this procedure the dry mixture of cement and aggregates is filled into the machine and conveyed with compressed air through the hoses. The water needed for the hydration is added at the nozzle.

The use of the wet-mix method began after the Second World War. Similar to ordinary concrete the mixes are prepared with all necessary water for hydration. The mixes are pumped by suitable machines through the hoses. At the nozzle compressed air is added for spraying.

Some people maintain that sprayed concrete is a special concrete. Basically, however, sprayed concrete is but one of several ways to cast concrete. As with traditional methods of casting, sprayed concrete also makes its special demands on the characteristics of the concrete during casting. At the same time all normal concrete technological demands, such as w/c ratio, amount of cement, correct consistency and after-treatment must be complied with and followed. The reason why so much sprayed concrete of poor quality has been applied in many parts of the world is because one seems to forget that sprayed concrete is only a way of casting and that all concrete technological requirements have to be fulfilled.

The equipment both for dry-mix and wet-mix sprayed concrete has been improved substantially. The present state of the art will be shown in a separate chapter.

1.2 Where is sprayed concrete used?

The enormous advantages of sprayed concrete as a construction process and the improvement of equipment, materials and application know-how have made it an important tool for various types of work.

Sprayed concrete takes care of stability problems in tunnels and other underground constructions. Today sprayed concrete is a key factor for rock support in
- Tunnelling
- Mining operations
- Hydropower projects
- Slope stabilization

More than 90 % of all sprayed concrete is used for rock support.

In comparison with traditional concrete, sprayed concrete is used today to a relatively small extent, but when it is used, it is done so in many different ways. Some examples:
- Pit curbing
- Canal lining
- Reconstruction and repair
- Sea walls
- Refractory
- Fire and corrosion protection
- Spraying of new constructions
- Agriculture (manure pits)
- Plastering and stabilizing of brick walls

Sprayed concrete is the building method of the future due to
- Flexibility
- Rapidity
- Economy

Only use your imagination – there are no limitations....

1.3 Sprayed concrete know-how

There are a few major sprayed concrete consumers who from practical experience, research and development have acquired know-how.

Equipment and control methods have also gone through a development which has led to a rational production as well as a more uniform quality of the final product. From an international point of view it is safe to say that we have come a long way from when sprayed concrete was used for securing rock, but it is also fair to say that we are lagging behind when using sprayed concrete for building and repair works. It is not easy to find a reason. The know-how exists, however, it is not fully utilised.

Figure 1: Remote-controlled spraying

Prevailing regulations make special concrete technological demands on the people doing the spraying work. Present requirements have led to a better training of involved personnel. The result of this is an improved quality of the work. The number of special contractors who are working with sprayed concrete has increased over the last few years, which improved the quality of the application. However, there is a risk of getting badly executed work by less serious contractors. This is particularly the case with smaller jobs where the contractor often lacks knowledge about sprayed concrete. These are, however, things that can be eliminated if the contractor makes more stringent demands for his competence, previous experience, trained personnel, knowledge about concrete and authorisation.

The contractors should demand an authorisation arrangement for sprayed concrete with general validity as it exists e.g. for casting and sheathing (like the Sprayed Concrete Association in UK).

1.4 Two methods – What is the difference?

Today, two spraying methods are common: dry-mix and wet-mix. With the dry-mix process the water required for hydration is added at the spraying nozzle, with the wet-mix method the conveyed mixtures already contain the necessary water for hydration.

Both methods have their advantages and disadvantages. Depending on the project requirements and the experience of people the best suited method should be chosen. There will be a need for both methods in the future.

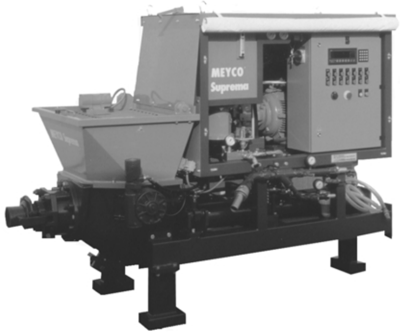


Figure 2: The MEYCO® Suprema offers pulsation-free spraying and a computerised control system (PLC).

Until a few years ago, dry spraying has been the dominating method, but this has changed, especially in sprayed concrete for rock support. In the future, we believe that wet spraying will be more and more prevailing as this method gives a better working environment, a higher and more consistent quality and a much higher production.

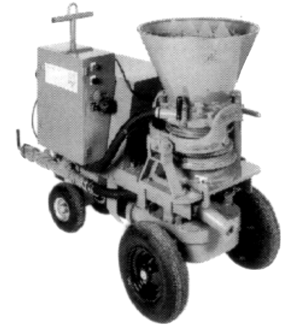


Figure 3: The MEYCO® Piccola excels by its sturdiness, the simple operation and its adaptability to the specific conditions on the site.

Future developments within the sprayed concrete technology will, we believe, be mainly in connection with the wet-mix process. Good examples of recent developments are the addition of new generations of additives (Delvo®crete, MEYCO® TCC, concrete improver (internal curing), microsilica and steel fibres) to the sprayed concrete.

The situation nowadays is that world-wide 70% of the sprayed concrete is applied by the wet-mix method and 30% by the dry-mix method. In some areas, however, the wet-mix method is already dominating (Scandinavia, Italy: almost 100 %). Within the next 5 years the wet-mix method could be used for more than 80-90% of all sprayed concrete world-wide. Today, more than 8 million m^3 of sprayed concrete are applied world-wide every year.

2. Dry-mix method

2.1 Composition of a dry mix

2.1.1 Cement content

For the manufacture of the dry mix, the proportion of the binder is usually between 250 and 450 kg per 1000 litres of aggregate or 320 to 460 kg per m^3 of concrete. In order to judge the actual cement content of the sprayed concrete applied, the rebound must be considered. In comparison with the initial mix, rebound mainly leads to a loss of top-size aggregate and thus to an increase in the cement content. In a typical standard mix with 350 kg of cement per m^3, a rebound of 20 % finally results in approximately 400 kg of cement per m^3 of in-place sprayed concrete.

2.1.2 Water/cement ratio

The water/cement ratio is, of course, a decisive factor for the quality of sprayed concrete. The total amount of water used with dry mixes is made up of the mixing water added at the nozzle and the moisture already in the aggregate. Unlike the wet spraying process, in the dry spraying process there is no clear-cut set value for the water/cement ratio, because the amount of mixing water is controlled and regulated by the nozzle man. This is frequently considered to be a great disadvantage. In practice, however, the water/cement factor is fairly constant, as there is a limited scope for varying the mixing water quantity: If too little water is added, the result is an immediate excess of dust; if too much water is added, the sprayed concrete does not adhere to the surface but runs down instead.

Where work is carried out properly, the water/cement factor varies only slightly and remains below 0.5. In the best case (aggregates requiring low water quantity, sufficient cement content), it is even possible to manufacture sprayed concrete with less than 0.4.

2.1.3 Natural moisture content

An important aspect of the dry mix is also the natural moisture content. Where the mix is too dry, spraying causes too much dust. If the natural moisture content is too high, this may lead to problems: The sprayed concrete throughput drops drastically, machines and conveying lines become encrusted and get blocked. Ideally, the natural moisture content should lie between 3 and 6 %.

In addition to on-site mixes, there has been an increase in the last few years in the use of dry materials delivered to the site in bags or in silos. Of course, these contain no natural moisture. To reduce dust formation it is advisable to wet the dry material before feeding it into the spraying machine. Specially equipped feeding devices or special pre-wetting nozzles can be used for this purpose.

2.1.4 Admixtures

Various admixtures are available for controlling the properties of sprayed concrete. The most important of these are fast setting admixtures (accelerators). These admixtures reduce the setting time. Sprayed concrete has a quicker setting and higher early strength. This allows subsequent layers of sprayed concrete to be applied sooner and in greater thicknesses.

On large-scale projects, accelerators definitely help to increase productivity and are an important pre-requisite for many applications. In underground construction works and pit curbing, for instance, the early strength of the sprayed concrete is decisive and an essential requirement.

As it is well-known from construction technology, accelerating the cement hydration inevitably results in a reduction of the 28-day strengths. In order to obtain a consistently high quality of sprayed concrete, it is thus essential to ensure that the lowest possible quantity of accelerator is added as consistently as possible. The accelerator proportion must be determined in each case in relation to the amount of cement used.

Accelerators can be used in powder or in liquid form. Powder accelerators (such as the alkali-free MEYCO® SA545) are added while feeding the spraying machine. Unfortunately, with the still widespread method of adding powder by hand, it is of course impossible to guarantee exact proportioning. The usual result is a massive overdose, very unevenly spread. Various studies have demonstrated a reduction of 35 % and more in the final strength compared to base concrete, i.e. without accelerator. Manual dosing can therefore only be accepted in exceptional cases or for sprayed concrete applications where quality requirements are low.

Greater precision is obtained with feeding devices combined with powder dosing appliances. The best results are achieved with feed screws equipped with a spindle batcher (e.g. MEYCO® Rig 016). Conveyor belt feeders are not recommended.

A convenient solution to the proportioning problem of powder accelerators is, of course, to use suitably modified bagged materials. However, these are often out of the question for financial reasons, especially in large projects.

The best way of ensuring the precise dosage of accelerator during application is to use liquid products (such as the alkali-free MEYCO® SA160). These are measured into the mixing water and thus added to the dry material at the nozzle. To obtain a steady dosage, however, it is essential to use a suitable dosing system even with liquid accelerators. Where it is necessary to pre-mix water and accelerator, machines are only suitable up to a point. Since the water/accelerator ratio is fixed, the dosage is altered in relation to the weight of the cement every time the water addition is adjusted by the nozzle man. However, it is both necessary and important to adjust the water quantity, for instance in order to respond to variations in the natural moisture of the aggregate or in the behaviour of the water flow on the surface.

A consistent cement/accelerator ratio can be ensured by using piston pumps, which measure a constant amount of the admixture defined in proportion to the capacity of the spraying machine quite independently of the water flow setting (e.g. MEYCO® Mixa).

Liquid accelerators have further advantages in comparison to powder: The problem of caustic components in the spray dust is avoided. Dosing at the nozzle prevents flash set. Thanks to the even mix with the spraying material, liquid accelerators can be measured more economically, which also leads to better final strengths. Experience shows that, compared to base concrete, the loss of final strength can be reduced to less than 25 %.

Apart from accelerators, the only other admixtures used in the dry spraying process are dust binders. These powder admixtures – as the name implies – reduce dust formation. In practice, however, these agents have only achieved limited acceptance.

2.1.5 Additives

Unlike chemical admixtures, the action of additives is mainly physical. Well-known examples are mineral fillers known as microsilica (or silica fume) which are more and more gaining in significance. These fine substances (surface of 20–35 m^2/g) with a proportion of SiO_2 varying from 65 to 97 %, depending on the quality of the product, lead to an important improvement in the quality of the sprayed concrete, apparent in the increased compressive strength and density. Due to the improved bonding, thicker layers can be sprayed even without accelerators.

In the dry-mix method microsilica have another interesting effect. Added in the proper way, the use of microsilica can also bring about a reduction in rebound of up to 50 %. With normal (uncompacted or densified) microsilica added in the mixer the rebound reduction is only minimal. Elkem has developed a special technology for adding a 50 % slurry at the nozzle (dosed in the water). The slurry system is very efficient but rather complicated. It needs a special dosing pump (e.g. MEYCO® Mixa) and an additional product on site in quite large quantities. The slurry has to be stored correctly and in most cases an agitator is necessary.

2.1.6 Fibres

For sprayed concrete, steel and synthetic fibres can be used. Their chief virtue lies in the fact that they lead to an improved fracture energy and/or shrinkage behaviour of the sprayed concrete.

The use of steel fibres is still relatively rare in dry-mix compared to wet-mix sprayed concrete. The main reason is the higher rebound (>50 %). Therefore, the cost/performance relation becomes critical. Thanks to the experience gained over the past few years and the present possibilities to reduce the rebound, however, the use of steel fibres is expected to rise also with the dry-mix method.

2.2 On-site mixes versus bagged materials

As already mentioned, the dry process allows the use of mixes with earth-dry or kiln-dried aggregates. Earth-dry aggregates are cheap and produce less dust. The natural moisture content is nevertheless sufficient to start off premature hydration. For this reason, earth-dry mixes have only a limited storage life and should be used up within 1 or 2 hours. Storage for a longer time causes an enormous increase in rebound and a heavy drop in final strength.

The manufacturing of the dry mix on site entails the installation of the necessary batching and feeding plants. Such an installation is obviously only worthwhile on large-scale projects. On a smaller scale or on short-term sprayed concrete projects the dry mix can be obtained from a ready-mix plant. This poses the problem of the increased delay before use due to the transport distance and the question of safe delivery. Delivery and placing must be very carefully scheduled in order to avoid delays and interruptions in the work due to inadequate supplies.

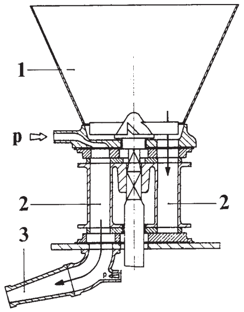
Of course, the greatest degree of flexibility possible is afforded by dry materials that are delivered in bags or silos. These can be stored over a long period of time, thus simplifying planning. Furthermore, they are also of consistently high quality. Disadvantages include the increased tendency to dust formation (which can be controlled by pre-wetting) and the considerably higher price.

The development of hydration control systems such as Delvo®crete has made it now possible to prolong the storage life of earth-dry mixes. By adding the Delvo®crete Stabilizer during manufacturing, the mix remains fresh and unchanged. The liquid Delvo®crete Activator S is added at the moment of the application. It simultaneously reactivates the cement hydration and acts as an accelerator. The Activator is added like a conventional liquid accelerator. Therefore technique and equipment have not to be changed when using Delvo®crete.

With the Delvo®crete Hydration Control System dry mixes can be stored for up to 3 days. This in turn means adequate flexibility in relation to bagged materials, but with considerably less costs.

2.3 Problem areas in the dry-mix spraying process

Every process naturally has its drawbacks. With the dry-mix spraying process, these are partially the relatively high costs due to wear and tear on the rotor machines, especially on rubber gaskets and friction discs.



1 = Feeding hopper
2 = Rotor
3 = Outlet
p = Pressurized air

Figure 4: The rotor principle of a typical dry-spraying machine (MEYCO® GM, Piccola)

By a correct set-up of the machines and by changing the parts in time (and with skilled grinding) these costs can be kept within reasonable limits.

Another disadvantage is the formation of dust. However, this can be considerably reduced by ensuring a favourable natural moisture content (or adequate pre-wetting) and by using dust binders. Water pressure boosting pumps can also help in this. These pumps intensify the water pressure during mixing at the nozzle. Combined with the use of improved water rings, it is possible to ensure good and steady wetting of the dry material at the nozzle. Depending on the system, the hydraulic pressure rises to about 80 bar. Such appliances are expensive and relatively susceptible to break down. In our experience, systems with 10–15 bar are usually fully adequate.

In addition to the formation of dust at the nozzle, the impact of the dust from the feeding system on the machine must be taken care of. In this respect, the traditional double-chamber machines or the modern version of Schürenberg (SBS) are advantageous. Rotor machines can, however, be dust-proofed to a large extent, or even completely, by various means, such as fitting a rotor dust collector or by continuously lubricating the rubber gaskets (intermittent lubrication).

Another way of completely sealing a rotor machine is to incorporate a hydraulic clamping system (e.g. as in the case of MEYCO® Unica). The rotor is sealed by means of a mantle and the clamping pressure is automatically adjusted to the feed pressure. This system guarantees the correct clamping pressure (even in the case of blockages or extreme feeding distances), thus ensuring that the machine remains sealed. This new type of clamping system also results in a significant reduction of the costs due to wear and tear and in the amount of compressed air required (approx. 25 % reduction).

Another important problem in the dry spraying process is the relatively high degree of rebound. Depending on the application surface (vertical or overhead), 15 to 35 % of concrete is lost. The average loss is 20 to 25 %, compared to between 5 and 10 % with the wet spraying process.

The rebound can be considerably reduced by using the new kinds of additives and admixtures mentioned above. Microsilica or hydration control systems like Delvo®crete have a positive effect. The average losses can thus be restricted to approx. 15 %, which is comparable to the results obtained with the wet spraying process.

The low performance of the equipment is frequently referred to as a further drawback. Nowadays, however, machines are available which make it possible to apply more than 10 m^3/h. This is of course no longer possible by manual application, but by the use of a spraying manipulator. However, due to the increase in wear costs, outputs in excess of 8 m^3/h become critical from an economical point of view.

2.4 Conclusion

Thanks to many years of experience in the dry spraying process, there is now a great deal of know-how available. It is extremely important to ensure that the materials, equipment and application techniques are selected and intermatched in the best possible way in order to achieve satisfactory results with regard to quality and economy.

The dry process is the older of the two spraying processes. Thanks to on-going developments in machine and material technology, it has been possible to keep extending the field of application. In the future it is to be expected that, due to the advantages and the opportunities available today for overcoming the traditional drawbacks, the dry spraying process will continue to play an important role. Main applications will be projects with relatively small volumes and/or high requirements as to flexibility (e.g. repair) or long conveying distances.

3. Wet-mix method

As mentioned earlier, this method is used 100 % in Scandinavia, Italy and in a large number of the major underground construction projects around the world. The considerable increase in the use of sprayed concrete for rock support over the last 15 to 20 years has made demands on the method and therefore the technology has gone through an intensive development.

The development in the wet-mix method in Scandinavia between 1971 and 1980 has caused the Scandinavian sprayed concrete market to turn upside down. During this period the sprayed concrete market turned from 100 % dry-mix spraying to 100 % wet-mix spraying. During the same period a similar change from manual to robot application took place. This dramatic change is unique to Norway. Since about 1976–1978 silica fume and steel fibres have been added to wet-mix sprayed concrete in rapidly increasing volumes.

It is not unfair to say that «Norwegians lead the way» into real wet-mix sprayed concrete, they are those who have definitely the longest experience and who know most about wet spraying.

Wet spraying received a bad reputation because of poor equipment and little knowledge of the method. Therefore, concrete of very poor quality was produced. In order to allow the mix to pass through the equipment, very high water contents were used, with w/c factors of up to 1.0. Thanks to the latest development in the concrete industry it is no problem nowadays to produce wet-mix sprayed concrete with compressive strengths of more than 60 MPa at 28 days.

Today, wet spraying is also used for the construction of new buildings (instead of traditional casting) and repairing of oil platforms in the North Sea. This is prove of the quality of the method as it is well-known that very stringent demands are made on methods and materials used in off-shore construction.

3.1 The reasons for the change to the wet-mix method

It is not known why the rapid change in Scandinavia has had no parallel in any other country. A description of the reasons under Norwegian conditions may give some explanation.

3.1.1 Economy

The spraying capacity has increased substantially from the dry-mix machines/ robots to the last stages of wet-mix robots. The practical average long term capacity per 8-hour shift is normally 4–5 times higher than that of the dry-mix method.

Investment cost for the new wet-mix robots increased dramatically, but as a matter of fact there was a parallel significant drop of the cost of in-place sprayed concrete. One of the main cost factors, the set-up time per spraying round, decreased. Due to integrated robot systems, the application of sprayed concrete can be started in a matter of minutes after arrival of the equipment on site. With the introduction of the hydraulic bore hammers the capacity of drilling increased by about 100 %. With higher investment less time is spent per round for drilling and blasting. Therefore, time cost increased. The time spent on spraying had to be as short as possible. Therefore the key factor was to increase the capacity of sprayed concrete application.

The reduction in rebound of about 1/4 per m^3 of sprayed concrete also had an important economical impact.

3.1.2 Working environment

When working with the dry-mix process the operators were used to a lot of dust. The dust emission was located not only at the nozzle, but also at the spraying machine. Measurements of dust in the working atmosphere normally gave results of more than three times of the amount allowed.

With the wet-mix method the change in the working atmosphere was evident and the crew would usually express their satisfaction with this improvement.

Spraying under severe rock conditions was one of the features that brought about the development of the wet-mix method. The safety risk was often unacceptable without a robot and the use of steel fibre reinforcement.

3.1.3 Quality

Quality is normally not considered as an asset of wet spraying nor as a reason to change from the dry to the wet method. We do not agree with those people stating that the wet-mix method produces bad quality and hence should be avoided. By using water-reducing admixtures (low w/c ratio) and microsilica, peak compressive strengths of wet sprayed concrete can be as high as 100 MPa.

The quality spread in wet-mix spraying is fairly stable with a low spread of results. With dry-mix spraying this is more problematic.

3.1.4 Application

With the wet method, a ready mixed concrete from a concrete plant is used, or a pre-bagged mortar is mixed. The concrete is prepared in the same way as for normal concrete. It is possible to check and control the w/c ratio and thus the quality at any time. The consistency can be adjusted e.g. by means of admixtures.

With the wet-mix method it is easier to produce a uniform quality throughout the spraying process. The ready mix is emptied into a pump and forwarded through the hose by pressure. At the beginning mainly mono (worm) pumps were used. Today, piston pumps are dominant and will be leading in the future.

At the nozzle at the end of the hose, air is added to the concrete at a rate of 7–15 m^3/min. and at a pressure of 7 bar depending on whether the spraying is performed manually or by robot. The air is added to increase the speed of the concrete so that good compaction is achieved as well as adherence to the surface. A mistake often made with the wet spraying method is that not enough air is used. Mostly only 4-8 m^3/min. are added which gives bad results for compressive strength, adherence and rebound. For robot spraying, up to 15 m^3/min. are necessary.

In addition to the air, set accelerators are added at the nozzle. Sceptics are wrong to maintain that frost-safe concrete cannot be obtained and that sprayed concrete with set accelerators gives a poorer bonding. Several well documented tests from public institutes and practical experience have shown that better frost proofing has been obtained than without accelerators due to the fact that a tighter and more durable concrete is obtained. Bonding is also improved by the accelerators because trickling is avoided and the concrete bonds immediately to the surface.

3.2 Advantages

The advantages of the wet-mix method compared to the dry-mix method can be summarised as follows:
- Far less rebound. A loss of 5–10 % is normal with use of correct equipment and trained personnel. These figures also apply to the spraying of fibre reinforced concrete.
- Better working environment; dust problem reduced.
- Thicker layers because of effective use of the admixing materials.
- Controlled water dosage (constant, defined w/c ratio).
- Improved bonding.
- Higher compressive strength and very little variation in results.
- Much larger production and consequently improved total economy.
- Use of steel fibres and new advanced admixtures.

3.3 Disadvantages

- Limited conveying distance (max. 300 m).
- Increased demands on aggregate quality.
- Only limited interruptions.
- Cleaning costs.

3.4 Summary of wet method

With robot spraying of sufficiently large surfaces, an average production of 60–100 m^3 may be achieved (with less than 10 % rebound) using the wet-mix method over a production time of 8 hours with one man.

Comparing dry and wet methods, one conclusion could be that the dry-mix method should be used for small volume applications (e.g. repairs) and in cases with very special conditions (long conveying distances, repeated interruptions etc.), whereas the wet-mix method should be used in all rock support works.

3.5 Mix design for wet spraying

Aids available for making good sprayed concrete with the wet-mix method:
- Cement
- Microsilica
- Aggregates
- Admixtures
- Liquid alkali-free set accelerators
- Fibres
- After-treatment
- Correct spraying equipment
- Correct execution

We shall briefly deal with the individual areas here in order to elucidate the advantages, but also point out drawbacks due to improper use. As mentioned earlier, the same requirements are made on sprayed concrete as on normal concrete for construction, namely
- Low w/c ratio
- Less water
- Less cement
- Good casting ability

The conflict between the properties of fresh concrete and set concrete is particularly strong for sprayed concrete and used to reduce the quality of wet-mix sprayed concrete. Water-reducing admixtures, as well as microsilica and fibres have, however, altered this.

3.5.1 Microsilica

Silica fume, or microsilica, is considered to be a very reactive pozzolan. It has a high capacity to incorporate foreign ions, particularly alkalis.

Microsilica has a definite filler effect in that it is believed to distribute the hydration products in a more homogeneous fashion in the available space. That leads to a concrete with reduced permeability, increased sulphate resistance and improved freezing and thawing durability.

When considering the properties of microsilica concrete, it is important to keep in mind that microsilica can be used in two ways:
- as a cement replacement, in order to obtain reduction in the cement content – usually for economic reasons.
- as an addition to improve concrete properties – both in fresh and hardened state.

In sprayed concrete, microsilica has to be used rather as an additive than as a substitute for cement to improve the concrete and spraying properties.

3.5.1.1 Special advantages of sprayed concrete with microsilica

Normal sprayed concrete qualities, i.e. 20–30 MPa cube strengths, can be produced without microsilica, whereas a practical and economical production of higher strengths is more or less dependent on the use of microsilica. It seems favourable from a technical point of view to use 5–10 % (by c.w.) of microsilica.

The correct use of microsilica can provide the sprayed concrete with the following properties:
- Better pumpability (lubricates and prevents bleeding and segregation)
- Reduced wear on the pumping equipment and hoses
- Increased cohesiveness of the fresh concrete and therefore reduced consumption of accelerator which is positive for the final compressive strength
- Increased bonding strength to various substrates and between sprayed concrete layers
- Improved strengths
- Improved resistance against alkali aggregate reaction

- Improved permeability resistance
- Reduced rebound
- Improved sulphate resistance

In fibre reinforced sprayed concrete it also provides:
- Easier mixing and distributing of fibres
- Reduced fibre rebound
- Improved bonding between cement matrix and fibres

Because of these positive effects we wish to maintain that microsilica should always be added to the sprayed concrete in order to obtain the best possible quality.

When adding microsilica to concrete because of its fineness it is necessary to add always a high rate of plasticizers/superplasticizers to disperse the microsilica. The dosage of admixtures increases by approximately 20 %, compared to sprayed concrete without microsilica.

3.5.2 Aggregates

As for all special concrete, the aggregate quality is of major importance for the fresh concrete as well as for the hardened product. It is particularly important that the grain size distribution and other characteristics show only small variations. Of particular importance are the amount and characteristics of fines, i.e. the grain size distribution and grain size analysis. However, it is not relevant to talk about choice of aggregate, as normally the available material must be used and the prescription has to be adapted to it. Nevertheless, for wet-mix spraying, the following criteria have to be observed:
- Maximum diameter: 8–10 mm. This is because of limitations in the pumping equipment and in order to avoid too much rebound loss. From a technological point of view, one should wish for a larger maximum diameter.
- The granule distribution basket is also very important, particularly its lower part. The fine material content in sieve no. 0.125 mm should be min. 4–5 % and not higher than 8–9 %.
- Too little fine material gives segregation, bad lubrication and risk of clogging. However, in the case of fibre concrete the surplus of fine material is important, both for pumping and compaction. A high fine material content will give a viscid concrete.

As the margins in the sieve basket are relatively small, it may often be convenient to combine two or more fractions, e.g. 0–2, 2–4 and 4–8 mm, by adjusting the proportion between them, to make a sieve curve that fits within the ideal curve limits. Too little fine material will be compensated by using more cement or microsilica. Too much fine material is primarily compensated by increasing the dosage of water-reducing admixtures.

The grain size distribution curve for the aggregate should fall within the striped area of Figure 5.

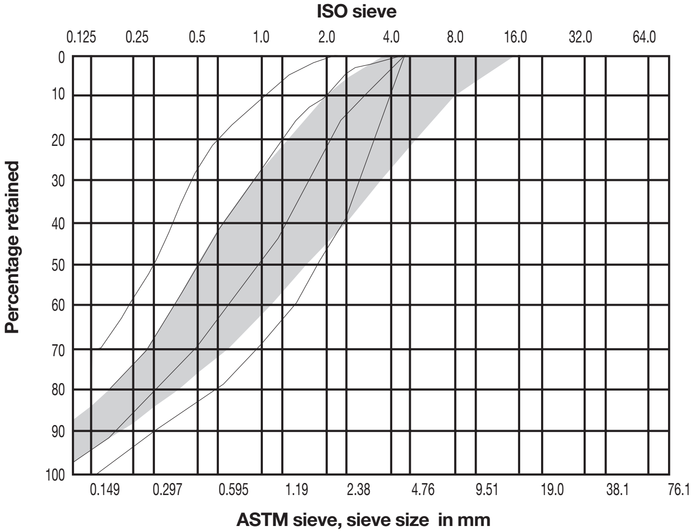


Figure 5

The quantity of 8 mm particles should preferably not exceed 10 %. The larger particles will rebound when spraying on a hard surface (when starting the application) or penetrate already placed concrete producing craters difficult to fill.

During screening, storing and handling of the aggregates, measures should be taken to prevent the presence of particles in excess of 8 mm. Coarse particles may block the nozzle and subsequent cleaning can be very time consuming.

Table 1:

SIEVE	MIN %	MAX %
0.125	4	12
0.25	11	26
0.50	22	50
1.0	37	72
2.0	55	90
4.0	73	100
8.0	90	100
16.0	100	100

The aggregates shall be well graded, and no fraction shall constitute more than 30 % of the total. The contents of crushed and non-cubical material should not exceed 10 %. An improvement of the grain size curve for a natural sand by the use of crushed materials often results in an increased water demand and poorer pumpability and compaction. Before crushed materials are employed as part of the aggregates, tests for comparison should be done to establish whether the addition of crushed material gives an improved result.

3.5.3 Admixtures (plasticizers/superplasticizers)

In order to obtain specific properties in the fresh and hardened concrete, concrete admixtures should always be used in the wet-mix spraying method. Concrete admixtures are no new inventions. The old Romans used different types of admixing material in their masonry, such as goat blood and pig fat in order to make it more mouldable. The effect must be good, since the constructions are still standing.

The fact is that concrete admixtures are older than PC-cement, but it is only during the last 30 years that more stringent requirements for higher quality and production have speeded up development, research and utilisation of admixing materials. Water reducers are used to improve concrete workability and cohesiveness in the plastic state. The water reducer can give a significant increase in slump with the same w/c ratio, or the w/c ratio can be reduced to achieve the same slump as for a mix not containing the water reducer. The reduced w/c ratio relates to a direct increase in strength. The higher slump adds to an increased pumpability.

The wet-mix method is attractive as the concrete is mixed and water is added under controlled and reproducible conditions, for instance at a concrete plant. The w/c ratio, one of the fundamental factors in the concrete technology, is under control. One often forgets, however, that the equipment makes heavy demands on the fresh concrete first of all in terms of pumpability. Furthermore, the method requires a larger amount of fast setting admixing materials, which may lead to loss of strengths in the final product.

Today, combinations of lignosulphonate, naphthalene and melamine are often used. This is to obtain the best possible and production-friendly concrete. Naphthalenes/melamines (superplasticizers) are chemically distinct from lignosulphonates (plasticizers/water reducers). They are better known as high range water reducers since they can be used at high dosages without the problems of set retardation or excessive air entrainment often associated with high rates of addition of conventional water reducers. Briefly, we can say that melamine forms a lubricating film on the particle surfaces, naphthalene electrically charges the cement particles so that they repel each other and lignosulphonate decreases the water surface tension. When well dispersed, the cement particles do not only flow around each other more easily but also coat the aggregates more completely. The result is a concrete that is both stronger and more workable.

The effect of superplasticizers/plasticizers to disperse «fines» makes them perfect and needed admixtures for sprayed concrete. The slump increase achieved by adding conventional superplasticizers is time and temperature dependent. However, pumpability can only be maintained for a limited time (20–90 min.) after mixing, and excessive dosages of admixtures can result in a total loss of cohesiveness and in segregation. Normal dosage is from 4–10 kg/m^3 depending on the quality requirements, w/c ratio, required consistency, as well as cement and aggregate type.

A new generation of high performance superplasticizers has entered the market during the last years. Glenium® is a high performance hyperplasticizer based on a modified polycarboxylic ether. It has the capability to provide a very high water reduction and excellent workability retention, without the usual unwanted set retarding side effect.

Glenium® is a complex and flexible molecule, comprising functional groups of chains of differing lengths. The mixing of water with cement initiates a chemical reaction (i.e. hydration). Water is absorbed into, and quickly dissolves, the surface of the cement particles. The Glenium® molecules are attracted to the surface of the cement particles during mixing and increase the negative charge on the surface, which causes electrostatic repulsion to occur. This results in greatly improved dispersion of the cement particles leading to a remarkable improvement in workability, despite the lower water content. The Glenium® molecules have very long side chains which also build steric hindrance, further improving the ability of the cement particles to keep a distance from each other and further increasing the dispersing effect.

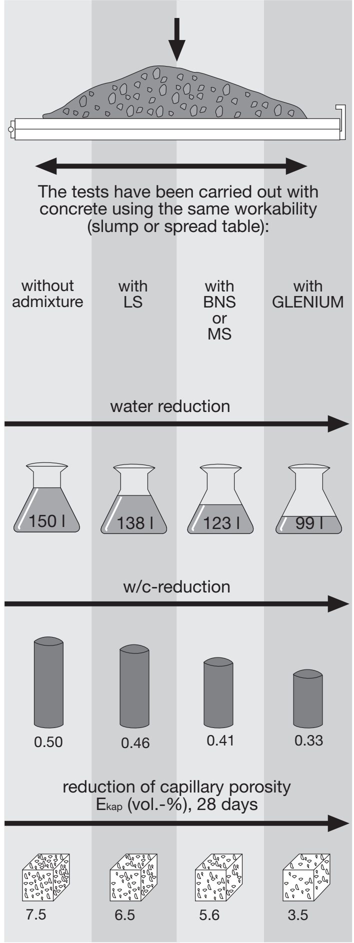


Figure 6: A comparison test on 28 days old concrete with various high range plasticizers reveals that Glenium produces by far the lowest capillary porosity compared to traditional superplasticizers.

Glenium® has a two step mechanism, which provides for an extended workability time for the fresh concrete. As part of the chemistry of Glenium®, a second molecule is incorporated which reacts after the first. The increasing alkalinity in the concrete during mixing and placing activates and drives the second molecule. This deferred action provides an extended workability without the usual side effects of retarded final setting times and retarded early strengths.

The benefits of Glenium® are:

- Extremely high water reduction (>40%)
- Low capillary porosity
- Long extended workability, with the lowest possible water/cement ratio
- High cohesiveness, easy pumpability
- Rapid strength development

Glenium®, a polycarboxylic, is already widely used in combination with alkali-free accelerators. It represents the future of sprayed concrete admixtures.

3.5.4 Traditional set accelerators

The wet-mix method requires the addition at the nozzle of accelerating admixtures for fast setting. The primary effect of these products is to reduce the slump (consistency) at the moment of spraying from liquid to paste while the concrete is still in the air, so that it will adhere to the surface as the layer thickness increases.

With the use of set accelerators, effective spraying on vertical and overhead surfaces becomes possible. The setting effect allows the application of sprayed concrete for initial support – an important function in the New Austrian Tunnelling Method (NATM). Water inflow (e.g. from the rock substrate) usually calls for a higher proportion of admixtures to accelerate the setting of sprayed concrete.

Accelerators are added in liquid form via a special dosing pump (piston or worm pump). The accelerator dosage may vary, depending on the operator’s skill, the surface and the water/cement ratio (high w/c ratios will increase the need for accelerators in order to reduce consistency).

Every coin has two sides. A secondary effect of traditional accelerators (based on aluminate and waterglass) is the reduction in final (28-day) strength compared to non-accelerated concrete. Therefore, the accelerator consumption should be kept at a minimum at all times (lower consumptions on walls than in the roof).

The difference between aluminates and modified sodium silicate/water-glass accelerators is basically that aluminate based set accelerators take part in the hydration process and contribute to higher early strengths within the first 0.5–2 hours (1–2 MPa).

3.5.4.1 How do aluminate accelerators work chemically in the hydration process?

Ground Portland cement clinker reacts with water spontaneously to a hardened mass which has a high compressive strength, already after a few minutes. Because of this quick reaction, these ground clinkers are only used in some special cases as bonding materials for concrete. To make them workable in the well-known way, 2–5 % of calcium sulphate ($CaSO_4$) have to be added.

This calcium sulphate reacts with the C_3A (tricalcium aluminate), one of the four important clinker phases to ettringite. The ettringite surrounds each cement particle like a dense coat which delays, but not really stops, the further access of water to the cement surface. Due to this retardation of the reaction of the cement paste, the concrete maintains its workability for a certain time. When all sulphates are consumed and bonded to ettringite, the excess of aluminates reacts with ettringite again and removes sulphates while building a «monosulphate». This monosulphate is more permeable to water which allows further cement reaction, in a quicker way, again.

By the addition of aluminate based set accelerators the required content of aluminates for the reaction to «monosulphates» will be raised suddenly. This allows normal cement hydration in a spontaneous way and leads to high early compressive strengths.

Normal setting characteristics for aluminate based accelerators are:

initial set:	<60 seconds*
end of set:	<3.5 minutes*

(* = Tested with manual vicat needle test machine and process.)

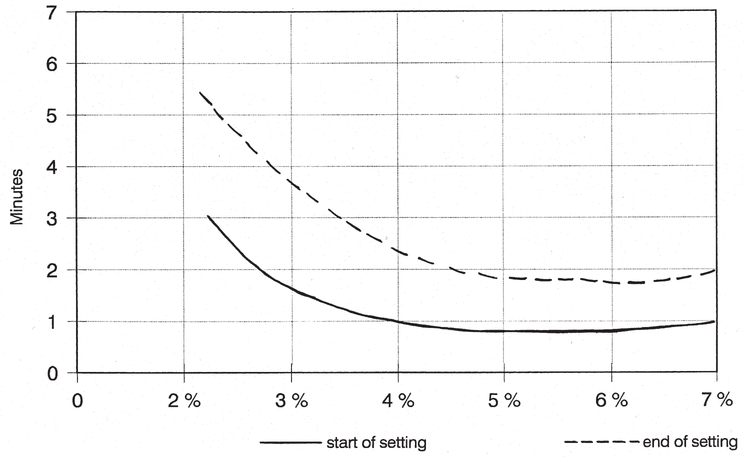


Figure 7: Setting behaviour of a high-efficiency aluminate based liquid accelerator

Aluminate based accelerators are preferably used in soft rock with heavy rock deformation and where high early strength support and large thicknesses (>15 cm) are required within a short time after the excavation.

Aluminate based accelerators start to develop strengths after 5–10 min. and after 20–30 min. the strength is normally high enough (>0.4 MPa) that the sprayed concrete layer is strong enough to bear its own weight. Therefore with aluminate based accelerators thicker layers can be sprayed than with modified sodium silicate or waterglass. Typical thicknesses can vary from 20–50 cm overhead.

Normal procedure is to spray a first layer of 6–10 cm in the whole area with each set up. By the time this is completed, strength has sufficiently developed so that going back to the starting point a new 10 cm layer can be sprayed. This process can be repeated until the required thickness is reached.

Aluminate based accelerators are also suitable to use where there are water problems. The normal spraying procedure with water problems is to put up a very thin layer of sprayed concrete with an overdose of aluminate accelerator (8–10 % b.w.) and to wait for 30 min. until this layer has developed sufficient strength to bear the water pressure. Spraying is continued until the required thickness is reached.

The disadvantages of aluminate based set accelerators are:

- Higher decrease in final strength than with modified sodium silicate (>30-50%)
- Very sensitive to type of cement, will not work with every type of cement. The reactivity of the cement has to be tested before spraying is started.
- Very high pH (>13) and therefore aggressive to skin, eyes etc.

Special precautions for handling and using this type of accelerator have to be observed. People involved in handling and spraying must always wear gloves, mask and goggles, and all direct contact with skin must be avoided.

Typical dosages of aluminate based set accelerators: 4–8 % of b.w.

There are two types of aluminate based set accelerators:

- Sodium aluminate
- Potassium aluminate

Potassium aluminate based accelerators work with a larger variety of cement types and normally give faster setting and higher early strength than sodium aluminate based accelerators.

Setting test with aluminate based accelerators

1) 30–32 g of water
2) 100 g of cement
3) Mix for 2–3 min. until a homogeneous cement paste is obtained.
4) Add 6 g of the accelerator to be used in the project.
5) Mix intensively by hand for a maximum of 15 seconds so that the accelerator is well distributed into the cement paste.
   Remark: Do not mix for more than 15 seconds, or it will spoil the setting characteristics.
6) Form a cake out of the accelerated cement paste and put it under the Vicat test machine.
7) Only use the manual (not automatic) Vicat needle machine.
8) Test the initial set and record it. The needle should stop at 1–2 mm from the bottom.
9) Test the end of set and record it. The needle may not penetrate into the cement paste.

Setting criteria

Initial set

<30 seconds	good
<60 seconds	acceptable
>60 seconds	not acceptable

End of set

<3 minutes	good
<4 minutes	acceptable
>4 minutes	not acceptable

Main criteria for aluminate based accelerators:

C_3A	5–10 %, preferably 7–9 %
Blaine	>3500, preferably >4000

Also depending on the blending of fly-ash, slag and gypsum.

3.5.4.2 Modified sodium silicates/water glass

Modified sodium silicates/water glass give only momentarily a gluing effect (<10 sec.) of the sprayed concrete mix (loss of slump) and take no part in the hydration process like aluminate based accelerators (if dosages do not exceed 20 % of b.w.)

Modified sodium silicates bind the water in the mix. Dosage is therefore depending on the w/c ratio: The higher the w/c ratio the more modified sodium silicate/water glass is required in order to glue the water and the mix.

Modified sodium silicates or water glass do not give very high strength within the first 2–4 hours. Normal final setting is from >30 min. (depending on cement type and temperature).

Advantages
- Work with all types of cement
- Less decrease in final strengths than with aluminate based accelerators at normal dosages (4–6 %)
- Very good gluing effect
- Environmentally friendly, not so aggressive for skin. The pH is <11.5, but still direct skin contact has to be avoided and gloves and goggles should always be used.
- Much lower alkali content than aluminate based products (<8.5% of Na_2O)

Disadvantages
- Temperature depending (cannot be used at temperatures below +5°C).
- Limited thickness: max. 8–15 cm

3.5.4.3 Fields of application

- For permanent support
- For temporary support, where no early strengths are required (hard rock conditions)
- Repair work
- In places where max. thickness of overhead application is limited to 10–15 cm

3.5.4.4 Typical dosages

Modified sodium silicates: 3–6 % by b.w.

Water glass should normally not be used because high dosages (>10–12 %, normally 20 %) are needed that decrease strengths and give a very bad quality and a false security. Normal water glass is more or less banned.

The European Specification for Sprayed Concrete (EFNARC) only allows a maximum dosage of 8 % by weight of the cementitious material for the use of liquid accelerators.

It is wrong, as some European sprayed concrete experts maintain, that there is a greater loss of quality with modified sodium silicate accelerators than with aluminate based accelerators. Their conclusion is only based on very few lab results with high dosages of waterglass (15–20 %) and a concrete with a w/c ratio of 0.7–0.8. This has no relevance for what is done in practice and it is therefore not right to draw any conclusion out of it.

The effect of modified sodium silicates in reducing final strength depends also on the curing conditions. At a dosage of 15 % of the cement weight, a 50 % strength loss could result; if samples are water cured, the loss is reduced to 30 %.

Long term tests with curing show final strengths equal to zero concrete (i.e. concrete without any accelerator). In most applications with a reasonable sodium silicate dosage (3–6 %) and a good quality control, not more than 20 % strength loss is acceptable. In practice the loss is between 10–15 %.

Note that an 18 year old wet-mix sprayed concrete recently tested in Norway has today the same strength as after 28 days. This is contradictory to what some people claim. The concrete quality with modified sodium silicate accelerators is not a problem up to 60 MPa.

3.5.5 Alkali-free sprayed concrete accelerators

Of late, safety and ecological concerns have become dominant in the sprayed concrete accelerator market and applicators have started to be reluctant to apply aggressive products. In France, Switzerland, Hong Kong, Singapore and Austria, e.g., it is no longer allowed to use caustic aluminate accelerators due to the health risk to personnel. According to information given in the ITA Working Group on Sprayed Concrete in Washington, 1996, one important reason for the large wet-mix market in Brazil is the health problems caused by dust in dry-mix spraying.

In addition, requirements for reliability and durability of concrete structures are increasing. Strength loss or leaching effects suspected to be caused by strong alkaline accelerators have forced our industry to provide answers and to develop products with better performances.

Traditionally, sprayed concrete operators have been used to excessive dust and health problems: skin burns, risk of loss of eyesight and even risk of injury due to falling rock (especially in the case of dry-mix manual spraying, with caustic aluminate accelerators and mesh reinforcement on unsupported ground). It is an international trend that these negative conditions are no longer accepted (with large local variations).

During the last decade the construction industry has been «crying-out» for safer sprayed concrete accelerators with better performance. Today, well functioning liquid alkali-free and non caustic products are available, providing safe, high quality and cost effective sprayed concrete applications. There is no longer an excuse for using dangerous products, such as the traditional caustic aluminates and caustic industrial waterglass. The author is in favour of totally forbidding these types of products. MBT is still selling caustic aluminates, but on direct request only, and no promotion activities are carried out any longer. As a consequence, the sales volume has been dramatically reduced and has been replaced by MBT's liquid alkali-free and non caustic accelerators.

The responsibility to improve the sprayed concrete application as well as the environmental and working safety now lies with the owners, the specifiers and the contractors.

Due to their complex chemistry, alkali-free accelerators are legitimately more expensive than traditional accelerators. However, accelerator prices have very little influence on the total cost of in-place sprayed concrete. Of much larger consequence are the time and rebound savings achieved, the enhancement of the quality and the safe working environment.

3.5.5.1 Dust development

The choice of the wet-mix method as well as the replacement of caustic aluminate accelerators by liquid non caustic and alkali-free products are big steps toward an improved working environment. Dust and rebound are dramatically reduced and skin burns can be made a matter of the past.

Dust measurements from the North Cape Tunnel in Norway (see case study in **chap. 3.5.5.10**) where high performance wet-mix sprayed concrete with the liquid non caustic alkali-free accelerator MEYCO® SA160 is used, show a total dust content of less than 3.7 mg per m^3 of air in the immediate environment of the operator. This value is two times lower than those of measurements obtained with liquid modified silicate accelerators, under the same conditions, see also Figure 8.

Direct comparisons by dust measurements under equal conditions in the same tunnel, are difficult to find. One example is the report by Dipl. Ing. Markus Testor from the Irlahüll Tunnel in Germany. The dust development was measured for three application systems:

1) Dry-mix process with oven dried aggregates mixed with Schwenk quick cement CEM I 32.5 R/SE, using a Rombold Spraymobile.
2) Dry-mix process with naturally humid aggregate and Heidelberg Cronolith S quick cement, using a Heidelberg Trixer with a SBS Type B1 spraying machine.

3) Wet-mix process with Karstadt CEM I 42.5 cement, liquid alkali-free accelerator MEYCO® SA140 and a MEYCO® Roadrunner Spraymobile.

The measurements were carried out with an optical fine dust instrument - hund TM DATA. The relative dust intensities measured in the immediate environment of the spraying operator were:

Spraying system	*Rel. dust intensity*	*Spraying capacity*	*Nozzles*
1) (dry)	12.6	13.5 m^3/h	2
2) (dry)	6.6	6.8 m^3/h	1
3) (wet)	3.3	15.4 m^3/h	1

Another example are dust measurements carried out in Scandinavia between 1979 and 1998, see Figure 8.

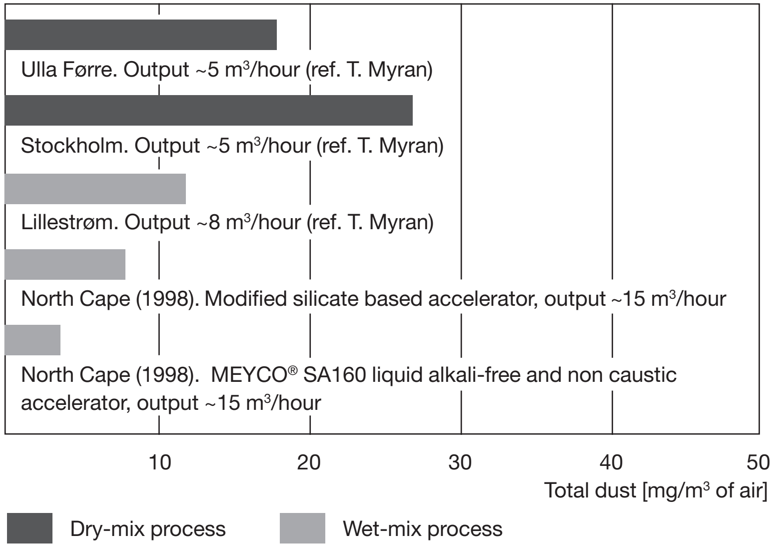


Figure 8: Comparison of dry-mix and wet-mix sprayed concrete, with different types of accelerators, based on some examples of dust measurements carried out in Scandinavia between 1979 and 1998. The application of the wet mixes in the North Cape Tunnel was carried out under identical conditions (equipment, operator, tunnel ventilation, spraying capacity and mix design).

3.5.5.2 Confusing chemistry: non caustic / alkali-free

In the context of sprayed concrete accelerators, the actual meaning of the terms *non caustic* and *alkali-free* are frequently mixed up. The reason for this is the dual meaning of *alkaline* in English professional language. The term *alkaline* can be understood as:

1) A basic liquid (with a pH value in the range of 7 to 14). As an example, calcium oxide dissolved in water produces a high concentration of OH^- ions and a pH value of about 13. This solution is strongly basic (= alkaline), but it contains no alkali cations.
2) A solution containing alkali cations such as Na^+, K^+, Li^+. An example is common salt dissolved in water (sodium chloride solution). This solution contains alkali cations; its pH value, however, is approx. 7, and it is therefore neutral.

Alkalinity and alkali content are two independent properties! For sprayed concrete accelerators the term *alkali-free* should have only one meaning: The accelerator contains no (or below 1%) alkali cations (see above, 2).

The reason to aim for this is that this will reduce the risk of alkali cations reacting with sensitive minerals (dissolvable silica, SiO_2) that are sometimes in the concrete aggregates. If such a reaction takes place, aggregate grains will fracture due to expansion. This may have a detrimental effect on the sprayed concrete matrix.

Most accelerators are strongly basic (pH value 12-14). This can be expressed as *caustic*, *basic*, *aggressive* or in some cases *corrosive*, however, the term *alkaline* should be avoided. There are also examples of accelerators that are strong acids (pH value 0-2). This can be expressed as *acidic*, *aggressive* or *corrosive*. The background for the importance of this property is working safety and working environment.

Strong acids as well as strong bases can be dangerous to personnel because of their aggressive behaviour upon contact with eyes, skin and the respiratory organs. The general terms to be used in this relation are therefore *near neutral* (pH value 5-9) and *aggressive* (pH value 0-4 and 10-14).

Table 2: Corrosiveness: The pH scale

0 ← acidic	**7** neutral	→ **14** basic (alkaline)
Aggressive/corrosive to: Steel Concrete Eyes and skin Respiratory organs	**Not corrosive** **and** ***not*** **aggressive**	**Aggressive/corrosive to:** Aluminium Eyes and skin Respiratory organs

Examples of pH values:

1	**4**	**7**	**10**	**12**	**14**
sulphuric acid, hydrochloric acid	acetic acid	water	soda, ammonia	cement milk	sodium hydroxide (caustic soda)

3.5.5.3 Non caustic alkali-free accelerators in liquid form

The increasing demand for accelerators for sprayed concrete termed *alkali-free* always contains one or more of the following issues:

1) Reduction of risk of alkali-aggregate reaction, by removing the alkali content arising from the use of the common caustic aluminate based accelerators.
2) Improvement of working safety by reduced aggressiveness of the accelerator in order to avoid skin burns, loss of eyesight and respiratory health problems.
3) Environmental protection by reducing the amount of released aggressive and other harmful components to ground water, from sprayed concrete and its rebound.
4) Reduced loss of sprayed concrete final strength, normally in the range of 15 to 50% with older accelerator products.

The focus within different markets, regarding the above points, is variable. Where most sprayed concrete is used for primary lining (in design considered temporary and not permanent), points 2 and 3 are the most important. When sprayed concrete is used for permanent structures, items 1 and 4 become equally important. This variation in basic reason why to require a new accelerator technology has caused some confusion.

Requirements in different countries, examples

In some countries almost all sprayed concrete in tunnelling is defined as temporary and is disregarded in the design of the permanent lining. The possible durability problems created by an alkali aggregate reaction in the sprayed concrete is therefore not an issue. There is, however, a growing demand for «alkali-free» accelerators, as legislation is being established, to improve working safety. In other words, the real requirement is for non aggressive accelerators.

In other countries the same use of sprayed concrete prevails, but there exist so far no regulations which prohibit aggressive accelerators. Out of concerns for environmental protection (= ground water) the authorities are, however, now requiring «alkali-free» accelerators. No additional high pH leaching components other than cement shall be used. The real requirement is in this case for a non aggressive (highly irritant) accelerator.

There are also countries where most sprayed concrete in tunnelling is temporary from a design point of view, but where, however, it is normal to require an «alkali-free» accelerator, i.e. non caustic and containing no alkali cations to avoid aggressive leaching components and, frequently, to obtain a limited allowed final strength reduction. Regarding personnel safety there exist so far no regulations against aggressive products.

Typical Situation I: The practical situation in the above cases is that of application directly at the tunnel face, mostly spraying on or through mesh reinforcement and lattice girders or steel beams, working on small areas at a time and quickly applying layer thicknesses of >150 mm. A high early strength is often mandatory for safety reasons.

In the *London* subway tunnelling the normal procedure when using sprayed concrete lining is to first apply a primary, temporary lining. So far there exist no regulations requiring the use of alkali-free accelerators for this. However, because of the very good results with temporary wet-mix sprayed concrete, the use of sprayed concrete also for the permanent lining is getting increased interest, as described by Annett and Varley. To produce a high quality, durable concrete with marginal final strength reduction, an «alkali-free» accelerator was required. In this case (Jubilee Line, Contract 104), the primary purpose of an alkali-free accelerator was that of durability and hence no alkali cations. Also at Heathrow Express Tunnel the first section of permanent sprayed concrete lining with alkali-free accelerator has been carried out. Especially in Scandinavia, but also more and more in other areas, permanent sprayed concrete linings are being applied in a separate construction phase, well behind the face area.

These examples could be summarized as **Typical Situation II:** The practical situation is that of a systematic application on relatively large areas, well behind the tunnel face, partly on mesh reinforcement and lattice girders, but to a growing extent using steel fibres. Final layer thicknesses may be large, but can be built in passes and a very high early strength is therefore not required.

In *Scandinavia* (shallow tunnels) the standard support solution can be termed as single-shell sprayed concrete lining or one-pass sprayed concrete lining. This approach is clearly getting increased attention also in other parts of the world. Basically, it means that the application of sprayed concrete at the face is carried out under quality requirements allowing it to be considered as part of the final and permanent sprayed concrete lining. »Single shell» means a single structure, which may well be produced in a number of steps (at the face and behind), see also chap. **9**. Road tunnels, railway tunnels, sub sea road and pipe tunnels, hydro power tunnels, the Gjøvik Olympic ice hockey rink etc. are examples of this approach in Norway.

In the case of single-shell permanent sprayed concrete linings both of the two typical situations described above apply. The basic difference is that the quality requirements are the same throughout the construction. The different practical requirements may call for different accelerators at the face and at later stages, depending on cement type and other local requirements. It has therefore become quite clear from tests with a range of different accelerators that it is not possible to cover all application situations with a single product.

Properties

MBT has made an important technology breakthrough with the launch of a range of liquid alkali-free and non caustic accelerators for both wet-mix and dry-mix sprayed concrete. With this step MBT puts itself ahead of the state of the art: Products in powder form are very difficult to use in practice.

Unlike most traditional accelerators, the alkali-free and non caustic products from MBT cause no or only minimal decrease in final strength. Requirements as demanded for HPS (durable sprayed concrete), e.g. for single shell permanent sprayed concrete linings, can be met more easily. But the most important innovation presented by the alkali-free accelerators launched by MBT is the safe working environment: No more danger of skin burns for the operators.

	MEYCO® SA160	**MEYCO® SA161**	**MEYCO® SA162**	**MEYCO® SA170**
Physical form (1)	liquid	liquid	liquid	liquid
Alkali cations (2)	<0.5%	<0.5%	<0.8%	<0.5%
pH value at +20°C, mixed 1:1 with water (3)	2.5-3.5	3.0-4.0	2.4-3.4	3.2-4.0
Layer thickness (4)	300 mm	300-500 mm	300-700 mm	300-700 mm
Dosage (5)	4-10%	3-8%	3-7%	3-7%
Early strength devel. (6)	good	very good	extremely good	extremely good
Corrosiveness (7)	high	high	moderate	none
Equipment (8)	stainless	stainless	stainless	standard
Effect on skin (9)	not classified	not classified	not classified	not classified
Handling (10)	simple	simple	simple	simple
Cement sensitive (11)	no	no	no	no

Comments:

(3) MEYCO® SA160/SA161/SA162/SA170 have a pH value of 2.5 to 4.0 and are therefore acidic. They are not aggressive enough to cause any skin problems, but MEYCO® SA160/SA161/SA162 are aggressive to steel and this requires acid resistant steel quality for equipment in direct contact with these products (before spraying). Once the alkali-free accelerators have been added at the nozzle, they are instantly neutralised by the alkali-rich cements. There is no corrosion risk to steel reinforcement.

(4) Minimum layer thickness that can be applied in the roof in one pass, provided a reasonably compatible cement quality has been chosen. With well suited cement types, these thicknesses can be substantially increased, although it is sound application technique not to push the limit. MEYCO® SA160/SA161/SA162/SA170 have proven to produce extremely large thicknesses, sometimes of up to 700 mm in one pass.

(5) The dosage is given as percentage by weight of binder (cement plus any pozzolanic additives). The lowest values indicated are achieved with good cements (high compatibility), while the maximum dosage may be used with poorer cements or if high early strength is required. It may be mentioned that dosages above the given maximum will produce no added quality, but can cause trickling and fall down and will reduce the final strength. Within the indicated dosage range there will be no or only marginal final

strength loss. In some cases the final strength is substantially higher than for the same concrete without accelerator.

(6) All products show excellent early strength development from about 1 hour upwards. The rating relates to the first few minutes and can be seen as a parallel to the possible layer thicknesses applied in the roof. MEYCO® SA160/SA161/SA162/SA170 are «very good» with almost all cements and are partly excellent (meaning as good as, or better, than best results of caustic aluminates).

(11) MEYCO® SA160/SA161/SA162/SA170 work with most cements. Even with blended cement types causing problems with all other accelerator types, they often work very well.

3.5.5.4 Alkali-free accelerators in powder form

The approach with powder products involves numerous practical limitations and constraints:

- Costs for an additional dosing unit
- One additional man for the dispensing of the accelerator into the dosing/dry spraying machine
- Higher dosages: approx. 7–10 % by b.w.
- More air to feed into the dosing unit (4–5 m^3/min.)
- Higher rebound. Experience from practical tests has shown that the rebound is 10–15 % higher as compared to liquid alkali-free accelerators.
- The approach with powder products is not practical in modern rapid tunnelling where wet-mix high performance steel fibre reinforced sprayed concrete plays an important role: The set up of the equipment between each spraying cycle is too complicated and too time consuming.
- In addition to all these practical and economical limitations and constraints, powder products also raise environmental concerns: They create a lot of dust and therefore cause a very bad working environment.

3.5.5.5 MEYCO® SA160/SA161/SA162/SA170: Sensitivity to type of cement

MEYCO® SA160/SA161/SA162/SA170 can be used with most (also blended and sulphate resistant) cement types (CEM I-IV). Compatibility tests with the cement(s) to be used are recommended for every sprayed concrete application with MEYCO® SA160/SA161/SA162/SA170 and before any practical concrete spraying.

Compatibility tests are carried out as follows:

Test of cement reactivity of alkali-free set accelerators (MEYCO® SA160/SA161/SA162/SA170)

In a cement paste:

(Equipment: mixing pot with rounded spatula, manual Vicat needle, stop-watch, testing cups)

1) 26-35 g of water
2) 1 g of Glenium® T801 or similar superplasticizer
3) 100 g of cement (+20°C ±1°C)
4) Mix very intensively until a homogeneous paste is obtained
5) Add 3-10 g of accelerator and mix for max. 5 sec
6) Immediately after mixing: fill up a test cup, place it under the manual Vicat needle and start measuring the penetration
7) Record initial set (needle stops 1-2 mm from the bottom of the cement mouse)
8) Record final set (needle cannot penetrate into the cement mouse)

Interpretation of results:

Initial set	<2 min	<4 min	>4 min
Final set	<5 min	<8 min	>8 min
Rating	good	acceptable	not acceptable

In a mortar (according to EN 196-1):

(Equipment: Hobbart mixer, manual Vicat needle, mortar prism forms)

1) Pour 195 g of water into the mixer, add 2-6 g of plasticizer (Glenium® T801 or similar) and 450 g of cement (+20°C ±1°C) and stir for 30 sec
2) Add 1350 g of norm sand and mix for 30 sec
3) Mix at medium speed for 30 sec
4) Stop for 90 sec
5) Mix again for 30 sec
6) Check the flow of the mortar (according to EN 196-1). Required flow: 15-18 cm. Adjust by adding water, if necessary
7) Add 3-10% of accelerator and mix for max. 15 sec
8) Immediately after mixing: prepare the test prism
9) Fill the prism form on a vibration table to avoid bad compaction
10) Place it under the manual Vicat needle and start measuring the penetration
11) Record initial set (needle stops 1-2 mm from the bottom of the cement mouse)
12) Record final set (needle cannot penetrate into the cement mouse)
13) Measure the compressive strength at 6 hours and at 24 hours

Interpretation of results:

Initial set	<2 min	2-5 min	>5 min
Final set	<6 min	8-13 min	>13 min
6-hour strength	2.5-4 MPa	1-2.5 MPa	<1 MPa
24-hour strength	18-25 MPa	10-18 MPa	<10 MPa
Rating	good	acceptable	not acceptable

Note:
If the setting times are bad, the 24-hour strength can still be good. Even with a slow setting it is possible to spray 5–7 cm on the wall or 3–5 cm overhead.

In most instances these tests do not work very well as the «gel» time is too fast for thorough mixing. MBT have developed a Viper test equipment to spray mortars for setting tests as a consequence.

3.5.5.6 Comparison of early strength results with traditional aluminate based accelerators

The formation of compressive strength and especially early strength is one of the most important parameters and properties of sprayed concrete used for rock support. It is, as well, one of the most important properties which can be changed by the addition of an accelerator. A series of tests have been done in order to position the new alkali-free MEYCO® SA accelerators. The early strength of sprayed concrete during the first 24 hours was measured for MEYCO® SA160 and traditional sprayed concrete accelerators used in the market (Delvo®crete Activator S71 (potassium aluminate) and S51 (sodium aluminate).

All accelerators were tested with the same mix design (w/c ratio, slump, etc.), and the tests were all sprayed from the same truck load. All spraying was done with MEYCO® Suprema and the same nozzle man. Curing conditions and temperature were the same for all accelerators. Testing of the early strengths was done with a MEYCO® Penetration Needle (up to 0.8–1.0 MPa) and with Hilti (from 1.0 MPa). All testings were done by the same person.

Results from the test

There is no significant difference in the strength formation between the different types of accelerators. It seems that the Delvo®crete Activators S71/S51 (aluminates) have a faster strength development in the first 1–2 hours but later the increase is much slower than that of the other accelerators. All accelerators have a drastic increase of the strength after 4–5 hours from 1–2 to 8–10 MPa. The highest 4–6-hour results were achieved with MEYCO® SA160.

Concrete mix design

Cement, type CEM I 42.5 (OPC)	425 kg
Aggregate (0-8 mm)	1713 kg
Rheobuild® 1000	1.5 %
Delvo®crete Stabilizer	0.2 %
w/c ratio	0.47–0.48
Slump	20 cm
Spread table	51 cm

Compressive strength measurements (at +20°C)

Type and dosage of accelerator	Strengths measured at: 15’	30’	1 h	4 h	6 h	12 h	24 h
Delvo®crete Activator S71							
4%	1.2	1.4	2.0	6.5	6.5	8	10.2
5%	1.0	1.0	1.2	6.5	6.5	7.5	10.6
Delvo®crete Activator S51							
4%	1.0	1.2	1.2	2.0	5.5	8.0	15.3
5%	1.0	1.2	1.2	2.0	4.0	7.5	14.4
MEYCO® SA160							
6%	0.5	0.7	0.8	0.9	6.0	20.0	20.5
9%	0.8	1.2	1.2	1.4	8.0	19.0	22.5

All results in MPa. MEYCO® Penetration Needle / Hilti.
10 measurements for each result.

Early strength development

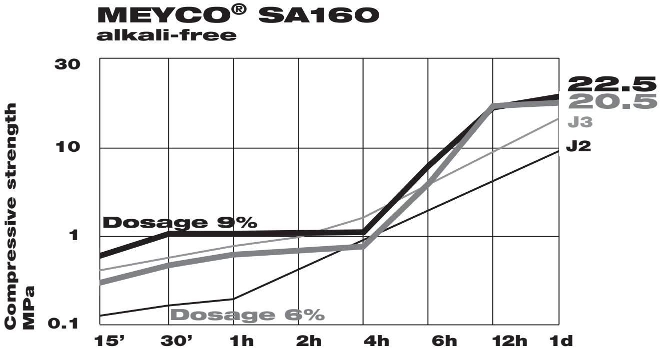


Figure 9: Early strength development of MEYCO® SA160 at +20°C

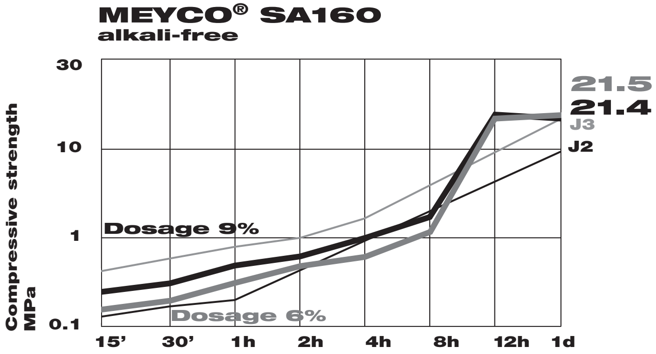


Figure 10: Early strength development of MEYCO® SA160 at <+10°C

3.5.5.7 Dosing and equipment

Dosing guidelines

Product	Dosage (c.w./b.w.)	Spraying method	Place to add
MEYCO® SA160	4-10%	wet	Preferably at the nozzle
MEYCO® SA160	3–10%	dry	At the nozzle together with the water (same as adding aluminate based accelerators)
MEYCO® SA161	3-8%	wet	Preferably at the nozzle
MEYCO® SA161	3–8%	dry	At the nozzle together with the water (same as adding aluminate based accelerators)
MEYCO® SA162	3-7%	wet	Always at the nozzle
MEYCO® SA162	3-7%	dry	At the nozzle together with the water (same as adding aluminate based accelerators)
MEYCO® SA170	3-7%	wet	Always at the nozzle
MEYCO® SA170	3-7%	dry	At the nozzle together with the water (same as adding aluminate based accelerators)
MEYCO® SA540/ SA545	5–10 %	dry	Manually or with a special powder dosing unit into the mix before feeding it into the spraying machine

Note: All equipment parts in immediate contact with MEYCO® SA160/SA161/SA162 must be made of stainless steel.

Cleaning of dosing pump with the use of MEYCO® SA160/SA161/SA162/SA170
With the use of MEYCO® SA160/SA161/SA162/SA170, the dosing pump, incl. sucking hose (valve) and accelerator hose, must be cleaned very well with water before spraying is started. It must be 100 % sure that the cleaning has been done (use a lot of water).

Every day, the whole system has also to be cleaned with water. Otherwise, there will be blockages in the dosing system. All people involved in tests with and usage of MEYCO® SA160/SA161/SA162/SA170 have to be informed about this.

Type of dosing system for MEYCO® SA160/SA161/SA162
MEYCO® SA160/SA161/SA162 are dispersions and therefore not all types of dosing pumps will work properly. In order to achieve a good result, it is of the utmost importance to secure a constant and adequate dosage.

We recommend the following types:

work very well:
- Mono pump
- Squeeze pump (Bredel)

can be used:
- Membrane pump

not to be used:
- Piston pumps
- All systems with seat valve system
- Pressure tank

When changing from one to another accelerator/activator, the whole dosing system must be cleaned properly (incl. sucking hose) in order to avoid any chemical reaction and clogging of the system.

Note:
Do not use a filter on the sucking hose as this causes obstructions. Avoid suction directly off the bottom of the drum/container.

Always use dosing equipment made of stainless steel or of other non corrosive material with the use of MEYCO® SA160/SA161/SA162.

3.5.5.8 Compatibility with other accelerators

Do not mix MEYCO® SA160/SA161/SA162/SA170 with other accelerators because this will cause immediate clogging of pumps and hoses.

Before using MEYCO® SA160/SA161/SA162/SA170, dosing pump, accelerator hose, nozzle and pulsation damper must be 100 % clean and free of any old products.

The same procedure must also be followed when changing from MEYCO® SA160/SA161/SA162/SA170 to other accelerators.

MEYCO® SA160/SA161/SA162/SA170 are compatible with each other, and no cleaning of equipment or hoses is required when changing within this product range. However, storage of mixed alkali-free accelerators is not recommended.

3.5.5.9 Special requirements for the use of MEYCO® SA160/SA161/SA162/SA170 for wet spraying

Mix design
- Minimum cement content: 400 kg, preferably 450 kg
- When used in wet spraying, the w/b ratio must always be in the range of 0.4 to 0.5. Humidity (water) contained in the aggregates must be taken into account!
  The lower the w/b ratio, the better the results achieved:
  - faster setting
  - higher early strengths
  - lower dosage
  - spraying of thicker layers overhead
  The results of a w/b ratio >0.5 are:
  - slower setting
  - lower early strengths
  - difficulty to apply layers of more than 5–7 cm; concrete will not stick to the rock substrate
- Temperature:
  Slower strength development at low temperatures when compared to other accelerator types.

Compatibility of MEYCO® SA160/SA161/SA162/SA170
All types of admixtures, including Delvo®crete Stabilizer, can be used with MEYCO® SA160/SA161/SA162/SA170.

Storage of MEYCO® SA160/SA161/SA162/SA170

Always stir prior to use. Do not store MEYCO® SA160/SA161/SA162 in steel tanks. MEYCO® SA170 does not require special storage precautions.

Safety precautions

MEYCO® SA160/SA161/SA162/SA170 are non caustic products and contain no hazardous substances which require labelling or special precautions.

3.5.5.10 Typical results from field tests

A) MEYCO® SA145

Heathrow Express, Contract C/D, London

OPC 42.5N	355 kg/m^3
Micro silica slurry	60 kg/m^3
Aggregate (0-8 mm)	1670 kg/m^3
Steel fibres (Dramix 30/50)	40 kg/m^3
Rheobuild® 2000PF	9.6 kg/m^3
Delvo®crete Stabilizer	4 kg/m^3
w/b ratio	$\leq$ 0.40
Addition at the nozzle:	
MEYCO® SA145	25 kg/m^3

Compressive strength:

	Robot spraying	Manual spraying
12 h	14.5 MPa	7.0 MPa
24 h	35.5 MPa	19.0 MPa
3 days	43.5 MPa	35.5 MPa
28 days	50 MPa	
100 days	58 MPa	
120 days	62 MPa	

The application by robot equipment has given substantially better strength results (100, 87 and 23% improvement at 12 h, 24 h and 3 days respectively). In our opinion this is caused by the improved compaction due to reduced work load and inconvenience for the nozzle operator in using correct application distance and angle.

B) MEYCO® SA160

Hüslen Tunnel, Switzerland

Cement 42.5 (Siggenthal), slow-setting	450 kg/m^3
Rheobuild® T3 (= superplasticizer + Delvo®crete Stabilizer)	1.2 % (hydration stop during 6 hours)
w/c ratio	0.41
Spread table	56 cm
Air temperature	+13°C
Thickness applied	150 mm
Addition at the nozzle:	
MEYCO® SA160	5%

Compressive strength:	
12 h (Hilti)	18.5 MPa
24 h (Hilti)	23.5 MPa
3 days	45.0 MPa
7 days	49.0 MPa
28 days	61.0 MPa

NEAT Intermediate Access Tunnel, Sedrun, Switzerland

Cement, CEM I 42.5	450 kg/m^3
Micro silica slurry	50 kg/m^3
Aggregate (0-8 mm)	1644 kg/m^3
Rheobuild® T3	1.2%
w/b ratio	0.47
Spread table	53 cm
Thickness applied	10-15 cm
Addition at the nozzle:	
MEYCO® SA160	5%
Rebound	<8%

Compressive strength:	
4 h	3.7 MPa
12 h	11.3 MPa
1 day	27 MPa
7 days	36.5 MPa
28 days	42 MPa
91 days	48.6 MPa

The Sedrun tunnel, lot 350, is a key part of the St. Gotthard Alp Transit Railway Project and consists of the four excavation faces of the one-lane tubes going North and South, a turn-out and the multi-purpose point in Sedrun.

The Gotthard Main Tunnel is designed to have a length of approx. 57 km, with two one-lane tubes without service tunnel. Its summit will be at 549 m above sea-level and is located south of the Sedrun shaft. Turn-outs are foreseen for service and maintenance purposes at Sedrun and Faido. Connecting tunnels between the two tubes are planned at intervals of 650 m; they will contain railway facilities and serve as emergency escapes.

NEAT Shaft, Sedrun, Switzerland

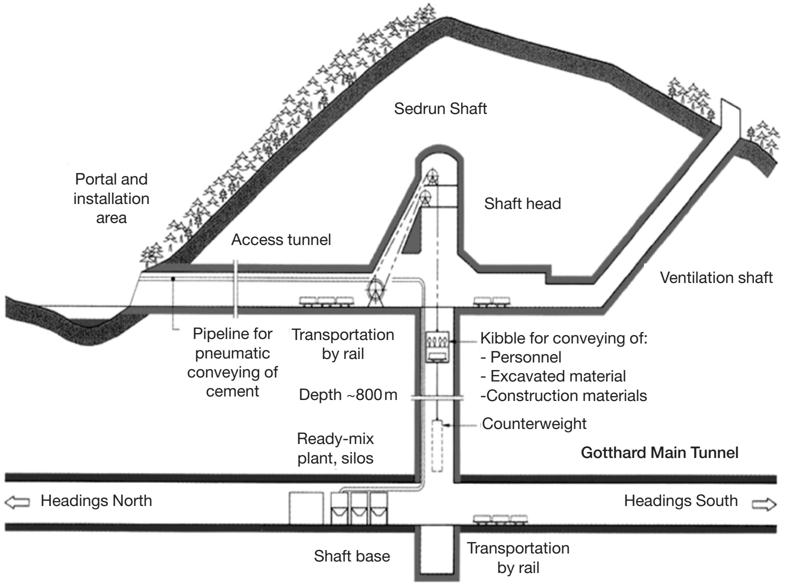


Figure 11: Sedrun Shaft

CEM II A-S 32.5R cement	450 kg/m^3
Elkem MS silica slurry	40 kg/m^3
Sand (0-4 mm)	1032 kg/m^3
Coarse aggregate (4-8 mm)	688 kg/m^3
Glenium® T803 (polycarboxylate)	5.4 kg/m^3
MEYCO® TCC780	2 kg/m^3
w/b ratio	~0.43
Spread table	>62 cm (after 4 h >58 cm)
Addition at the nozzle:	
MEYCO® SA160	6-8%

Compressive strength:	
6 min.	>0.2 MPa
30 min.	>0.5 MPa
1 h	1 MPa
4 h	>3 MPa
24 h	>15 MPa
28 days	>55 MPa

The Sedrun Shaft (depth 800 m, cross section 57 m^2) serves as a transport and access tunnel for the Gotthard Main Tunnel. Rock support: 5,000 m^3 of sprayed concrete (layer thickness 15 cm), dropped through 6” pipe. Lining: 7,000 m^3 of cast in-situ concrete (layer thickness 30 cm), dropped through 6” pipe.

Sieberg Tunnel, Austria

Cement, Gmunder PZ375 (H)	425 kg/m^3
Aggregate (0-8 mm)	1680 kg/m^3
Rheobuild® T3	1.2%
w/c ratio	0.45
Spread table	~60 cm
Addition at the nozzle:	
MEYCO® SA160	8-10%
Thickness applied	30-40 cm
Rebound	10-12%

Compressive strength:	
6 min.	0.25 MPa
18 min.	0.45 MPa
1 h	1.5 MPa
4 h	6-7 MPa
1 day	12 MPa
28 days	48 MPa

One of the first large projects in Austria where the wet-mix method is used. Volume: 25,000 m^3 of sprayed concrete.

The Sieberg Railway Tunnel is 6.5 km long, mostly in soft marls, with little overburden, sometimes only a few metres. Two intermediate access points allow excavation at 6 different faces. Rock support is done with 30-40 cm of sprayed concrete as primary lining and unreinforced cast concrete as permanent lining. The tunnel was originally started with dry-mix sprayed concrete, using a ready-mix of oven dried aggregates and quick-setting cement, blown with compressed air. The system was simple, but dust, rebound and cost went out of control.

Irlahüll Tunnel, Germany

CEM I 52.5 cement	380 kg/m^3
Fly-ash	50 kg/m^3
Sand (0-2 mm)	763 kg/m^3
Crushed aggregate (2-8 mm)	950 kg/m^3
Woerment FM785 (polycarboxylate)	0.6%
Woerment Lentan VZ31 (retarder)	0.3% (workability 3 h)
w/b ratio	0.5
Addition at the nozzle:	
MEYCO® SA160	8-10%

Compressive strength:	
6 min.	>0.3 MPa
30 min.	0.7 MPa
1 h	1 MPa
24 h	>15 MPa
28 days	>45 MPa

The Irlahüll Tunnel is part of the High Speed Railway Nuremberg - Ingolstadt. Tunnel length: 7,260 m. Geology: limestone, sandstone, with water table locally above tunnel crown. Excavation: drill & blast with top heading, bench and invert, up to 11 headings in parallel; cross section 150 m^2; advance length 0.8-2.0 m. Rock support: 20-40 cm of sprayed concrete using 10 MEYCO® Spraymobiles; with wire mesh reinforcement, systematic rock bolting and face support when required.

Galleria di Orte, Italy

CEM 42.5 cement	500 kg/m^3
MEYCO® MS610 silica fume	15 kg/m^3
Aggregate (0-8 mm)	1650 kg/m^3
Glenium® T801 (polycarboxylate)	0.8%
w/b ratio	0.45
Addition at the nozzle:	
MEYCO® SA160	6.5%
Thickness applied	25-40 cm
Rebound	<8%

Compressive strength:	
24 h	>14 MPa
2 days	>23 MPa
3 days	>27 MPa
7 days	>36 MPa
28 days	45 MPa

Requirements of the job: 10,000 m^3 of sprayed concrete to be applied in 9 weeks; layer thickness 200 - 300 mm. Results: Steel ribs were embedded with single pass layers of 50 mm; final set achieved in 4 minutes.

La Palma de Santa Cruz Tunnel, Palmas de Gran Canarias, Spain

CEM II 42.5 A - P cement	450 kg/m^3
Sand (0-6 mm)	1430 kg/m^3
Aggregate (6-12 mm)	260 kg/m^3
Rheobuild® 1000 EPS	7.6 kg/m^3
w/c ratio	0.40
Slump	14-16 cm
Thickness applied	20-30 cm
Addition at the nozzle:	
MEYCO® SA160	7-9%
Rebound	10%

Compressive strength:	
24 h	16 MPa
3 days (in situ cores)	22 MPa
28 days (in situ cores)	>30 MPa

North Downs Tunnel, Channel Tunnel Rail Link, UK

CEM I 52.5	360 kg/m^3
PFA	90 kg/m^3
Sand	1038 kg/m^3
Crushed aggregates	692 kg/m^3
Glenium® T801 (polycarboxylate)	3 kg/m^3
Delvo®crete Stabilizer	4 kg/m^3 (workability 6 h)
w/b ratio	<0.40
Target slump	200 mm
Addition at the nozzle:	
MEYCO® SA160	5% (average)
(top heading 5-7%, bench/invert 3.5-4.5%)	
Permeability (*in situ*)	1 x 10^{-12} m/s

Compressive strength:

6 min.	>0.18 MPa
30 min.	>0.3 MPa
1 h	>0.5 MPa
24 h	19.5 MPa
3 days	26 MPa
28 days	>36 MPa
56 days	>42 MPa

The North Downs Tunnel is a single-bore twin-track tunnel; excavation cross section 140 m^2, length approx. 3.5 km. Characteristics: 120 year design life; sprayed concrete primary layer; cast *in situ* concrete secondary layer; waterproof and fire resistant; client and contractor adopting permanent sprayed concrete philosophy.

North Cape Tunnel, Norway

Cement, CEM I 52.5R	520 kg/m^3
Micro silica	25 kg/m^3
Aggregate (0-8 mm)	1700 kg/m^3
EE steel fibres (25 mm)	50 kg/m^3
Plasticizer (lignosulphonate)	2.5 kg/m^3
Superplasticizer (melamine)	4-5 kg/m^3
Delvo®crete Stabilizer	2 kg/m^3
MEYCO® TCC735	5 kg/m^3
w/b ratio	0.45
Slump	20-21 cm
Addition at the nozzle:	
MEYCO® SA160	8%
Thickness applied	25-50 cm
Rebound	<5%

Compressive strength:

1 h	>2 MPa
4 h	>7 MPa
24 h	>30 MPa
28 days	>40 MPa

Half of the tunnel is in extremely poor shale, causing a lot of overbreak. The original approach consisted of a full in situ concrete lining per round (round length: 2 m), with an average concrete thickness of >1 m. The key to the success was that uninterrupted spraying of any thickness, at high capacity, was possible. With the above mix design an average layer thickness of 250 mm was sprayed, at 36-42 m^3 per round, placed in 2-2.5 hours. This resulted in a 2-3 times faster advance rate of 30-45 m per week and face. The required 28-day strength of 30 MPa was exceeded by far.

Station at Oslo National Theatre, Norway

Test. Contractor: Selmer ASA. Equipment: MEYCO® Roadrunner.

Cement 52.5	500 kg/m^3
Micro silica	25 kg/m^3
Aggregate (0-9 mm)	1530 kg/m^3
Rheobuild® 716	8.25 kg/m^3
Delvo®crete Stabilizer	2 kg/m^3
w/b ratio	0.42
Slump	~20 cm
Addition at the nozzle:	
MEYCO® SA160	8%

Compressive strength:

30 min.	>1.0 MPa
1 h	>2.2 MPa
2 h	>4.5 MPa
4 h	>9 MPa
28 days	>50 MPa

Sveti Marko Tunnel, Slovenia

Cement, PC-30-45S	450 kg/m^3
River sand (0-1 mm)	260 kg/m^3
Crushed sand (0-4 mm)	780 kg/m^3
Gravel (4-8 mm)	690 kg/m^3
Glenium® T801 (polycarboxylate)	0.42%
Delvo®crete Stabilizer	0.18%
w/c ratio	0.48
Addition at the nozzle:	
MEYCO® SA160	8%

Compressive strength:

24 h	20 MPa
28 days	45 MPa

Completely weathered rock. Construction with continuous pipe roof throughout the tunnel.

Bolu Tunnel, Anatolian Motorway Project, Turkey

CEM 42.5 cement	500 kg/m^3
Silica fume	25 kg/m^3
Aggregate (0-5 mm)	1186 kg/m^3
Aggregate (5-12 mm)	474 kg/m^3
Steel fibres	50 kg/m^3
Rheobuild® 716	10 kg/m^3

w/b ratio	0.42
Addition at the nozzle:	
MEYCO® SA160	35 kg/m^3

Compressive strength:	
4 h (Hilti)	5.2 MPa
8 h (Hilti)	12.2 MPa
12 h (Hilti)	13.9 MPa
24 h (*in situ* cores)	15.5 MPa
3 days (*in situ* cores)	31.8 MPa
7 days (*in situ* cores)	42.5 MPa
28 days (*in situ* cores)	55.8 MPa

Difficult soil conditions - clayey metasediments and blocky flyschoid; unexpected extreme plastic behaviour of soil; deformations exceeding limits; extended thrust faults from tectonic point of view - required high early and final strength.

South Deep Shaft Sinking Project, Johannesburg, South Africa

CEM I 52.5 cement	475 kg/m^3
Fly-ash (Super Poz)	75 kg/m^3
Silica fume	38 kg/m^3
Stella sand (river sand, 0-2 mm)	160 kg/m^3
Crusher sand	1080 kg/m^3
Stone (6, 7 mm)	262 kg/m^3
Fibrin Monofilament fibres	0.9 kg/m^3
Dramix stainless steel fibres	40 kg/m^3
Delvo®crete	4.0 kg/m^3
MEYCO® TCC735	5.0 kg/m^3
Glenium® T801 (polycarboxylate)	4.6 kg/m^3
w/b ratio	0.36
Addition at the nozzle:	
MEYCO® SA160	6-7%

Compressive strength:	
24 hours	15 MPa
2 days	30 MPa
3 days	56 MPa
7 days	76 MPa
28 days	86 MPa
56 days	95 MPa

Shaft sinking (final shaft depth 3,000 m, 9 m in diameter) through pre-extracted and backfilled shaft pillar at 2,335 m to access massive orebody at depths of >2,500 m. Special requirements: good slump retention for discharge from kibble; fast setting to apply up to 100 mm/pass in very wet «rain» conditions; high durability in difficult maintenance area; high ductility to prevent spalling due to ground movement; early strength gain to prevent strain bursts.

Sondu Miriu Hydro Electric Power Plant, Kenya

Bamburi OPC Type 1	422 kg/m^3
River sand	966 kg/m^3
Crushed aggregate (5 - 10 mm)	655 kg/m^3
Glenium® T803 (polycarboxylate)	0.45%
w/c ratio	<0.45
Slump	100 mm
Air content	5.5%
Addition at the nozzle:	
MEYCO® SA160	7%

Compressive strength:	
24 h	11.5 MPa
3 days	22 MPa
28 days	32 MPa

The access to the project location is very difficult. Sprayed concrete is used as temporary lining prior to concrete final lining.

Quarry Bay Station, MTRC Contract 680, Hong Kong

OPC 42.5	400 kg/m^3
Micro silica	40 kg/m^3
Fly-ash	60 kg/m^3
Aggregate (0-10 mm)	1640 kg/m^3
Rheobuild® 561	10 kg/m^3
w/b ratio	0.40
Slump	20 cm
Addition at the nozzle:	
MEYCO® SA160	6%
Thickness applied	20 cm

Compressive strength:	
8 h	13.5 MPa
1 day	23 MPa
7 days	35 MPa
28 days	52 MPa

Contractor: Nishimatsu Construction Company Ltd. Equipment: Aliva Duplo 285 spraying machine, MEYCO® Mix 200 dosing unit and MEYCO® nozzle system.

Blackhill Tunnels, MTRC Contract 603, Hong Kong

OPC	350 kg/m^3
PFA	110 kg/m^3
Crushed rock filler	1065 kg/m^3
Aggregate (10 mm)	540 kg/m^3
Rheobuild® 561	5.5-6 kg/m^3
w/b ratio	<0.45
Addition at the nozzle:	
MEYCO® SA160	6-7%

Compressive strength:	
7 days	25 MPa
28 days	38-40 MPa

The contract involves approx. 8 km of drill and blast tunnel, with complex centre sidings, cross-overs and enlargements.

Tai Lam Tunnels, KCRC West Rail Contract No. DB350, Hong Kong

OPC	345 kg/m^3
PFA	115 kg/m^3
River sand	615 kg/m^3
Crushed rock fines	410 kg/m^3
Aggregate (10 mm)	565 kg/m^3
Dramix ZP305 steel fibres	45 kg/m^3
Rheobuild® 561	5.5 kg/m^3
Delvo®crete Stabilizer	2.0-4.0 kg/m^3
w/b ratio	0.45
Addition at the nozzle:	
MEYCO® SA160	26 kg/m^3

Compressive strength:	
24 h	12 MPa
28 days	28 MPa

Contractor: Nishimatsu Construction Company Ltd. Twin track single tube railway tunnel, using MEYCO® Spraymobiles. Some 8,000 m^3 of sprayed concrete reinforced with Dramix ZP305 steel fibres are anticipated.

Rock Caverns, Singapore

Cement	470 kg/m^3
MB-SF silica fume	20 kg/m^3
Sand	720 kg/m^3
Chipping	610 kg/m^3
Crushed rock filler	220 kg/m^3
Steel fibres	56 kg/m^3
Glenium® T803 (polycarboxylate)	3.4 kg/m^3
Delvo®crete Stabilizer	1.7 kg/m^3 (workability 3 h)
w/b ratio	<0.42
Target slump at batching plant	180 ±20 mm
Addition at the nozzle:	
MEYCO® SA160	5-7%
Steel fibre rebound	7%

Compressive strength:	
7 days (trials)	29-32 MPa
28 days (trials)	37-41 MPa
28 days (production)	43-44 MPa

Dali Baoshan Highway, China

Cement 42.5R	420 kg/m^3
Aggregate (0-10 mm)	1700 kg/m^3
Dramix steel fibres	50 kg/m^3
Rheobuild® 561	1%
w/c ratio	0.45
Addition at the nozzle:	
MEYCO® SA160	5%

Compressive strength:	
24 h	>25 MPa
28 days	>40 MPa

The main benefit by using MEYCO® SA160 is related to the geological conditions of this project - swelling clay. Sufficient layer thickness can be achieved in a one layer pass and the required early strength can be gained.

Burnley and Domain Tunnels, Melbourne City Link, Australia

OPC	430 kg/m^3
Micro silica	20 kg/m^3
Aggregate (0-8 mm)	1680 kg/m^3
BHP steel fibres (25 mm)	50 kg/m^3

Pozzolith® 370	4.8 kg/m^3
Rheobuild® 716	4.8 kg/m^3
w/b ratio	0.40
Slump	14 cm
Addition at the nozzle:	
MEYCO® SA160	8%
Rebound	<10%

Compressive strength (*in situ* cores):

1 day	18 MPa
7 days	34 MPa
28 days	48 MPa

The Burnley Tunnel will be 3.4 km long and at its deepest point 65 m below ground. The Domain Tunnel will be 1.6 km long and 25 m below ground at its deepest point. Upon completion, each tunnel will be 11.5 m in width, with a height clearance of 4.9 m. The tunnels were supported by pre-shaped steel arches and steel bolts grouted in pre-bored holes, all covered with a temporary sprayed concrete lining, applied through four MEYCO® Spraymobiles.

Cameron Run Tunnel, Virginia (U.S.)

Cement	420 kg/m^3
Sand	1290 kg/m^3
Coarse aggregate	480 kg/m^3
Xorex 38 mm steel fibres	35 kg/m^3
Polyheed 997	0.8%
w/c ratio	0.42
Addition at the nozzle:	
MEYCO® SA160	8%

Compressive strength:

24 h	13.7 MPa

Repair of overflow tunnel underneath live railroad tracks with shallow overburden. The project includes jacking the steel lining back into original shape and re-lining with steel ribs and steel fibre reinforced sprayed concrete. Early strength development is crucial.

Dulles Airport Pedestrian Walkback Tunnel, Virginia (U.S.)

Cement	470 kg/m^3
Sand	1170 kg/m^3
Coarse aggregate	525 kg/m^3
Xorex 38 mm steel fibres	40 kg/m^3
Polyheed 997	0.8%
Delvo®crete Stabilizer	1%
w/c ratio	0.39
Addition at the nozzle:	
MEYCO® SA160	6%

Compressive strength:

10 h	14 MPa
24 h	19.3 MPa

The tunnel (diameter 5 m, length 300 m) will be excavated using the NATM method. Due to its location underneath live taxiways, early strength development is crucial.

NuMI Tunnel, Illinois (U.S.)

Cement	440 kg/m^3
Sand	1150 kg/m^3
Coarse aggregate	565 kg/m^3
Xorex 38 mm steel fibres	60 kg/m^3
Rheomac SF100	30 kg/m^3
Polyheed 997	1%
Delvo®crete Stabilizer	0.5-2%
w/c ratio	0.45
Addition at the nozzle:	
MEYCO® SA160	6%

Compressive strength:

8 h	10.3 MPa

Fermi Laboratories is constructing an accelerator tunnel for the purpose of splitting the atom. This TBM tunnel (diameter 7 m, length 1.8 km) will utilize sprayed concrete for initial (with steel fibres) and final lining (without reinforcement).

Belo Horizonte Metro, Brazil

OPC	400 kg/m^3
Aggregate (0-12 mm)	1686 kg/m^3
Mastermix® 390	1 kg/m^3
Rheobuild® 716	3 kg/m^3
w/c ratio	0.45
Slump	10 cm
Addition at the nozzle:	
MEYCO® SA160	8%
Thickness applied	20 cm
Rebound	<10%
Compressive strength:	
3 days	19 MPa
7 days	24 MPa
28 days	32 MPa

Figure 12: The sprayed concrete in the Heliopolis tunnel, which is part of the Belo Horizonte Metro, was applied through a MEYCO® Roadrunner.

Buenavista Tunnel, Villavicencio, Colombia

OPC, CEM I 42.5	460 kg/m^3
Micro silica	19 kg/m^3
Aggregate (0-16 mm)	1770 kg/m^3
Rheobuild® 716	7.2 kg/m^3
w/b ratio	0.39
Slump	18-20 cm
Addition at the nozzle:	
MEYCO® SA160	6%
Thickness applied	20 cm
Compressive strength:	
10 min.	0.7 MPa
24 h	14 MPa
28 days	39 MPa

Road tunnel with a length of 4.9 km. Sprayed concrete volume: 10,000 m^3. Contractor: Recchi G.L.F.

Miel 1, Hydroelectric Power Project, Colombia

DEUNA CEM II 52.5 A/B cement	370 kg/m^3
Fly-ash	20 kg/m^3
Pulverized limestone	50 kg/m^3
Aggregate (0-8 mm)	1285 kg/m^3
Aggregate (5-12 mm)	474 kg/m^3
Mappei 404 superplasticizer	1.0%
Mappei retarder	0.3%
w/b ratio	0.50
Addition at the nozzle:	
MEYCO® SA160	8%
Compressive strength:	
30 min.	>0.5 MPa
1 h	>0.6 MPa
6 h	>1.9 MPa
14 h	>5.6 MPa
28 days (*in situ* cores)	>26 MPa

Lo Prado 2 and Zapata 2 Tunnels, Chile

Melón AR cement	400 kg/m^3
Aggregate (0 - 8 mm)	1760 kg/m^3
Dramix RC-65/35-BN steel fibres	40 kg/m^3
Pozzolith® 322N	0.5%
Rheobuild® 1000 EPS	1.5%
Delvo®crete Stabilizer	0.4%
w/c ratio	0.46
Slump	>15 cm
Addition at the nozzle:	
MEYCO® SA160	7%
Rebound	<5%

Compressive strength:	
4 h	>1 MPa
24 h	>20 MPa
28 days	>40 MPa

To increase the capacity of the Ruta 68, between Santiago de Chile and the cities of Valparaiso and Viña del Mar, two new tunnels (cross-section 72 m^2, lengths 2,700 m - Lo Prado 2 and 700 m - Zapata 2) are built parallel to the existing ones. Lining is carried out as a single-shell sprayed concrete lining.

C) MEYCO® SA161

Lærdal Tunnel, Norway

Cement, CEM 42.5	439 kg/m^3
Micro silica	30 kg/m^3
Aggregate (0-8 mm)	1670 kg/m^3
Dramix steel fibres 30/50	44 kg/m^3
Glenium® T803	2.7 kg/m^3
MEYCO® TCC735	5 kg/m^3
w/b ratio	0.42
Slump	20-22 cm
Addition at the nozzle:	
MEYCO® SA161	7.5%
Thickness applied	10-15 cm
Rebound	<5%

Compressive strength:	
30 min.	0.8-0.9 MPa
28 days	~42 MPa

With a final length of 24 km the Lærdal Tunnel is today the world's longest road tunnel. The tunnel has a very high overburden and some substantial rock bursting occurred during the excavation. To overcome these and other problems and to reduce cracks in the sprayed concrete, the original mix design was adjusted and the performance of the concrete significantly improved.

Frøya Tunnel, Norway

Cement, CEM 42.5	480 kg/m^3
Micro silica	33 kg/m^3
Aggregate (0-10 mm)	1530 kg/m^3
Dramix 30/50 steel fibres	44 kg/m^3
Glenium® T801	1.8 kg/m^3
MEYCO® TCC735	5 kg/m^3
w/b ratio	0.38
Slump	16-17 cm
Addition at the nozzle:	
MEYCO® SA161	7.5%
Thickness applied	15-25 cm
Rebound	5-6%

Compressive strength:	
15-20 min.	1 MPa
28 days (*in situ* cores)	47 MPa

Subsea road tunnel through extremely difficult zones with heavy water ingress and extremely bad rock. Tunnel length: 7 km.

Hamaoka Nuclear Power Station, Japan

Cement	380 kg/m^3
Sand (0-4 mm)	1124 kg/m^3
Aggregate (4-10 mm)	726 kg/m^3
NT 1000 (polycarboxylate)	1.25%
w/c ratio	<0.50
Slump at batching plant	17 cm
Air content	4.5%
Addition at the nozzle:	
MEYCO® SA161	5% (average)

Compressive strength:	
3 h	>1 MPa
24 h	>6.5 MPa
7 days	>24 MPa
28 days	>34 MPa

The construction of an additional nuclear reactor required a cable tunnel (cross-section 14.6 m^2, length 400 m). Sprayed concrete at a layer thickness of 150 mm was used for initial support.

Shirogane Dai Subway Station in Tokyo, Japan

Cement	450 kg/m^3
Sand (0-4 mm)	1113 kg/m^3
Aggregate (4-8 mm)	500 kg/m^3
Bridgestone steel fibres 30/60	40 kg/m^3
NT 1000 (polycarboxylate)	1.7%
Delvo®crete Stabilizer	1%
w/c ratio	0.40
Addition at the nozzle:	
MEYCO® SA161	8%

Compressive strength:	
3 h	>3.6 MPa
24 h	>13.9 MPa
7 days	>32 MPa
28 days	>42 MPa

Sprayed concrete for corrosion and fire proofing of steel lining in the station area. The layer thickness varied from 80 - 400 mm, all concrete being sprayed in a single pass onto the steel surface.

D) MEYCO® SA162

S. Giacomo Tunnel in Bolzano, Italy

II AL 42.5 cement	480 kg/m^3
Aggregate (0-8 mm)	1560 kg/m^3
Rheobuild® 5000	1.5%
w/c ratio	<0.47
Addition at the nozzle:	
MEYCO® SA162	8%
Thickness applied	40-80 cm
Single layer thickness	15-20 cm
Rebound	<5%
Initial setting time	45-60 min.

Compressive strength:	
6 min.	>0.4 MPa
10 min.	>0.55 MPa
20 min.	>0.7 MPa
30 min.	>0.85 MPa
1 h	>1.2 MPa
5 h	>4.5 MPa
24 h	>12 MPa
28 days	>32 MPa

2.3 km road tunnel. Technical specifications in accordance with Austrian Norms (SpB 25 - 56/II/J2). Very low temperatures in winter. Excavation by drilling and blasting through igneous rock, with overbreaks of up to 80 cm and more. Work progress: 24 m^3 per hour.

E) MEYCO® SA170

Kienberg Tunnel, Austria

CEM II/A-S 42.5R cement	420 kg/m^3
Aggregates: 0.1-0.4 mm crushed	105 kg/m^3
0-4 mm round	650 kg/m^3
0-4 mm crushed	470 kg/m^3
4-8 mm crushed	525 kg/m^3
Glenium® 51 (polycarboxylate)	0.5%
Delvo®crete Stabilizer	0.5% (workability 4-5 h)
w/c ratio	0.48
Addition at the nozzle:	
MEYCO® SA170	7%

Compressive strength:	
6 min.	>0.25 MPa
1 h	>0.8 MPa
24 h	>14 MPa
7 days	>28 MPa
28 days	>38 MPa

The 1.5 km twin tube two lane Kienberg Tunnel is part of the Pfyrn Motorway in Upper Austria. It is driven through closely fractured and jointed rock. Typical rock support for a 1.3 m round consists of forepoling, lattice girder, double wire mesh, 20 cm of sprayed concrete and 4-6 m long fully grouted rock bolts.

The performance of the sprayed concrete was crucial due to the high excavation speed (6 rounds per day) and the increased layer thickness required by frequent overbreaks. Rock bolting and drilling for forepoling took place immediately after the sprayed concrete application. The early strength development had to fulfil the requirements of the Austrian Norm J2.

Strengen Tunnel, Austria

CEM II/A-S 42.5R cement	420 kg/m^3
Aggregates: 0-4 mm crushed	1380 kg/m^3
4-8 mm crushed	450 kg/m^3
Glenium® 51 (polycarboxylate)	0.5%
w/c ratio	0.45
Addition at the nozzle:	
MEYCO® SA170	5.5%

Compressive strength:	
6 min.	>0.3 MPa
1 h	>0.9 MPa
24 h	>15 MPa
7 days	>36 MPa
28 days	>48 MPa

The 5.8 km twin tube two lane Strengen Bypass Tunnel is the last part of the East-West motorway connection in Austria. Each tube has a typical cross section of 80 m^2, which is excavated as top heading and bench by drilling and blasting. The rock mass consists mainly of highly metamorphic, laminated and sheared rock (quartz phyllite). Typical rock support for a 1.5 m round consists of lattice girder, double wire mesh, 20 cm of sprayed concrete and 4-6 m long fully grouted rock bolts.
The early strength development had to fulfil the requirements of the Austrian Norm J2. The overall accelerator consumption could be kept very low.

Blisadona Tunnel, Austria

PZ 375 cement	420 kg/m^3
Aggregate (0-2, 0-4, 4-11 mm)	1750 kg/m^3
Glenium® T801 (polycarboxylate)	0.6-0.7%
Delvo®crete Stabilizer 10	0.4% (workability 7 h)
w/c ratio	<0.5
Addition at the nozzle:	
MEYCO® SA170	7.5% (average)

Compressive strength:	
6 min. (Hilti)	>0.32 MPa
10 min. (Hilti)	>0.42 MPa
30 min. (Hilti)	>0.59 MPa
1 h (Hilti)	>0.78 MPa
3 h (Hilti)	>2.6 MPa
6 h (Hilti)	>5 MPa
12 h (Hilti)	>8 MPa
24 h (Hilti)	>20 MPa
7 days (*in situ* cores)	25 MPa
28 days (*in situ* cores)	31 MPa

2.4 km double track railway tunnel west of the Arlberg Tunnel. Heavy water ingress called for use of extremely fast setting concrete mix.

Girsberg Tunnel, Switzerland

CEM I 42.5 cement	425 kg/m^3
Sand (0-4 mm)	1060 kg/m^3
Natural round aggregate (4-8 mm)	640 kg/m^3
Rheobuild® T3	1%
w/c ratio	0.47
Addition at the nozzle:	
MEYCO® SA170	6%

Compressive strength:	
6 min.	>0.3 MPa
30 min.	>0.8 MPa
1 h	>1 MPa
24 h	>15 MPa
28 days	>55 MPa

The Girsberg Tunnel is part of the Highway Kreuzlingen - Constance. The rock conditions are very difficult, with fast weathering clayey marl and heavy water ingress.

4. New advanced sprayed concrete admixture systems

4.1 Synopsis

With urban land becoming scarcer and the environmental impact of infrastructure projects being a prime consideration, more and more public utilities and transportation systems are being constructed underground. Because of this, the use of sprayed concrete is increasing on a world-wide basis.

Traditional sprayed concrete is a compromise between early and final strength values, flexibility and economic viability. However, the development of new generations of admixtures has led to essential improvements and to new application fields of sprayed concrete.

In the following, two new technologies will be presented, which have been developed by MBT:

- The hydration control system Delvo®crete which has heralded the way to a much greater flexibility and higher quality for the utilization of sprayed concrete and has considerably furthered the wet-mix spraying method, thus contributing to better working conditions and lower cost through reduced dust and rebound.
- A new system to secure efficient and reliable curing of sprayed concrete.

4.2 Delvo®crete

The supply and utilization of sprayed concrete mixes for infrastructure projects in congested environments creates problems for both the contractor and ready-mixed concrete supplier.

Sprayed concrete mixes, wet or dry, only have a useful «pot-life» of 1.5 to 2 hours and even less at temperatures above +20°C. Material sprayed after this time will exhibit lower strengths and increased rebound, due to the commencement of hydration of the cement.

Long trucking distances from the batching plant to the site, delays in construction sequences as well as plant and equipment breakdowns ensure that much of the concrete actually sprayed is beyond its «pot-life».

In addition to this, environmental regulations may well impose restrictions upon the working hours of batching plants in urban areas, meaning that a contractor who requires sprayed concrete mixes to be supplied 24 hours per day, may only be able to obtain material for 12 hours each day.

Problems such as these create unnecessary additional costs of construction for both the contractor and the client.

A chemical system for the controlling of cement hydration in both wet and dry sprayed concrete mixes has been developed by MBT, enabling the working life of such mixes to be substantially increased.

4.2.1 Introduction

The development by MBT of a two-component, liquid, chloride-free hydration control system for returned waste concrete and the recycling of concrete truck mixer wash water in 1987 enabled many concrete producers to eliminate the problems associated with waste concrete from their batching plants. The first component of this system is known as the «Delvo® Stabilizer», which is capable of inhibiting the hydration of Portland cements for periods of up to 72 hours. The second component of the system is the «Delvo® Activator», which is a hydration accelerator that is added to the stabilized concrete before placing.

In 1989, MBT adapted the hydration control system for use in sprayed concrete. The «Delvo®crete Stabilizer» component is similar to that used for returned concrete, and a range of «Delvo®crete Activators» were developed for the initiation of cement hydration. The «Delvo®crete Activators» are added to the sprayed concrete mix at the spraying nozzle in exactly the same way as conventional aluminate or silicate based accelerators for fast setting and high early strengths that are required in rock support applications.

The Delvo®crete system, which was first used commercially in Europe in 1990, enables the «pot-life» of sprayed concrete mixes, both wet and dry, to be extended for periods of up to 72 hours. This eliminates many of the problems and headaches associated with the production and application of consistent, high quality sprayed concrete mixes encountered by contractors, concrete producers and engineers.

The Delvo®crete hydration control system is able to give flexibility to the production and spraying of concrete mixes in large underground projects and, at the same time, offers considerable cost savings to contractors, owners and concrete producers.

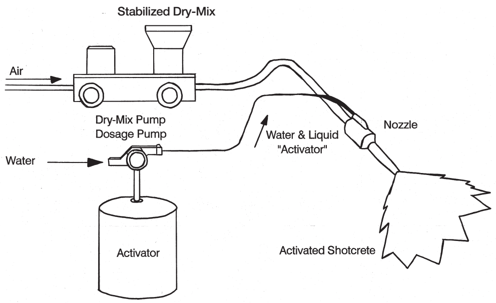


Figure 13: Hydration controlled dry-mix sprayed concrete

It also ensures that all sprayed concrete which is sprayed through the nozzle contains a «fresh» cement that has undergone little or no hydration reactions.

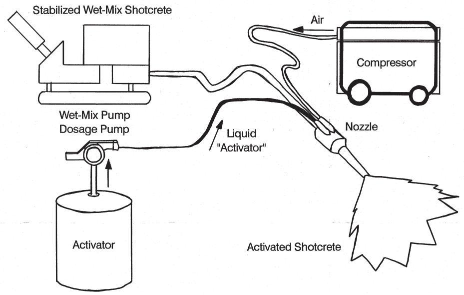


Figure 14: Hydration controlled wet-mix sprayed concrete

The system brings revolutionary benefits to sprayed concrete (in particular wet-mix sprayed concrete) and is currently being used on a lot of big projects in Europe, America, the Middle East and Far East.

4.2.2 Wet-mix sprayed concrete

Wet-mix sprayed concrete has a definite advantage over dry-mix sprayed concrete in that it is a genuine concrete, and, as such, the w/c ratio is controlled at the batching plant and is independent of the nozzle man.

Wet mixes also have a «pot-life» of approximately 1.5 to 2 hours. This means that the concrete mix should be pumped and sprayed very quickly after batching. On large underground construction projects, this is not always possible. Long trucking times from the batching plant to the point of spraying and application, as well as delays and breakdowns of equipment at the excavation face, ensure that a very large proportion of the sprayed concrete is beyond its «pot-life» when it is applied.

With wet-mix sprayed concrete in rock support jobs, an experienced nozzle man, spraying a well designed, accelerated fresh concrete will probably achieve rebound values of between 10 % and 15 % overall. Similar figures can be obtained when robotic spraying systems are employed.

Traditional wet-mix sprayed concrete has therefore been a compromise between high slump, low w/c ratio, long pot-life, fast setting and high early strength. This has always created problems for contractors, concrete suppliers and clients. It creates large amounts of waste material from rebound, the washing out of pumps and hoses and the dumping of sprayed concrete quantities that have lost their workability (i.e. too old). The waste material then has to be removed from the underground excavation, carted away and dumped. All this creates unnecessary additional costs to the contractor, who will have budgeted for a certain percentage of rebound and overspray, but probably not for the hauling and dumping of waste material, nor for the waste created when loads of sprayed concrete have to be dumped, and pumps and hoses have to be washed out, when equipment breakdowns and delays cause interruptions to spraying at the excavation face.

4.2.3 Batching and delivery of wet-mix sprayed concrete

The batching of sprayed concrete mixes itself should create no problem for a good, experienced concrete supplier. However, the location of the batching plant in relation to the project site is critical.

In many urban areas, the erection of concrete batching plants is not permitted. Since most large underground infrastructure projects, such as tunnels and metro systems, are in densely populated urban areas, often concrete mixes have to be hauled for long distances from outlying plants before delivery on site. Consequently, much of the «pot-life» of the sprayed concrete has already expired before it arrives on site and is discharged. Add to this, the time taken to spray a full truck load of sprayed concrete, as well as any delays that may occur on site, then it is easy to see that a great deal of sprayed concrete applied in underground urban infrastructure projects is of questionable quality.

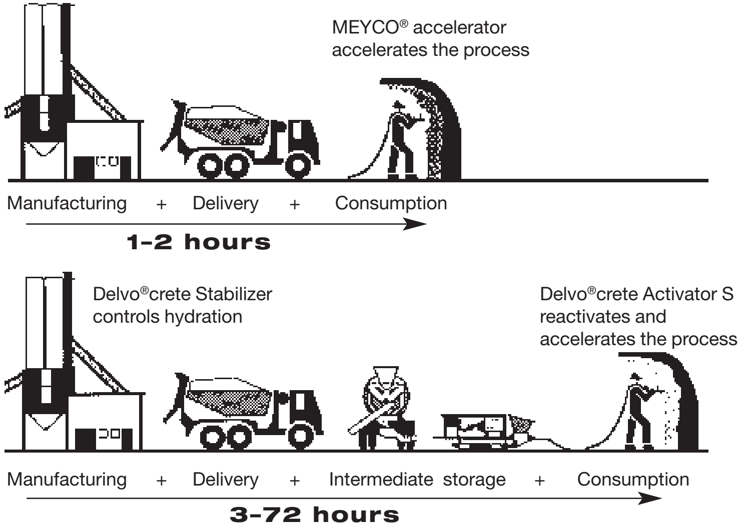


Figure 15: Delvo®crete for total flexibility in sprayed concrete

Even if an urban underground project has obtained the space and permission to erect a site batching plant, local environmental restrictions may well limit the working hours of such a plant to day time only. In such a case, it will be impossible for a project that is working 24 hours per day, seven days per week, to obtain supplies of sprayed concrete at night.

In order to solve some of the logistical problems associated with the delivery of sprayed concrete to underground projects and ensure that a fresh concrete mix is supplied to be sprayed at the rock face, some equipment manufacturers have developed transportable mixers, or «trixers».

In simple terms, «trixers» constitute a mini batching plant mounted on the back of a suitable carrier vehicle or truck. «Trixers» contain separate compartments for storing cement, aggregates and water. The «trixer» is loaded with materials at a batching plant, or storage location, and then driven into the underground excavation. Upon arrival at the excavation face, the materials are batched and mixed together to produce a fresh sprayed concrete mix. This can either be a wet or dry mix.

A limitation of the «trixer» is that it can normally hold only enough material to batch approximately 6 m^3 of sprayed concrete. It follows then, that in any project in which say 10 m^3 of sprayed concrete is being sprayed per hour with a spraying robot, a minimum of two «trixer» units will be required to service the robot. If more than two faces are being worked on at the same time, then even more «trixers» will be required.

4.2.4 Control of cement hydration

The setting, hardening and strength characteristics of Portland cement are achieved by the reaction of the cement with water. The product of this reaction is a rigid material known as calcium silicate hydrate (or CSH) gel.

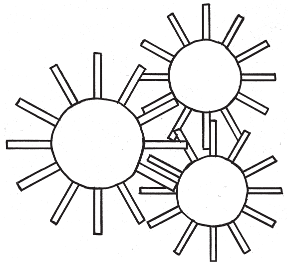


Figure 16: As concrete or sprayed concrete sets, hydrates formed by cement hydration flocculate.

This reaction is known as hydration, which, in simple terms, produces a rapid release of calcium ions into solution and forms a CSH gel shell around the cement grains. As concrete sets, hydrates formed by cement hydration flocculate, and it is this process which turns plastic, workable concrete into a stiff material (Figure 16).

By adding the Delvo®crete Stabilizer to a concrete mix, the hydration of cement may be completely controlled for periods of up to 3 days. The Delvo®crete Stabilizer, when dispensed and thoroughly dispersed into a concrete mix, controls the rate of hydration of the cement by complexing calcium ions on the surface of the cement grains (Figure 17).

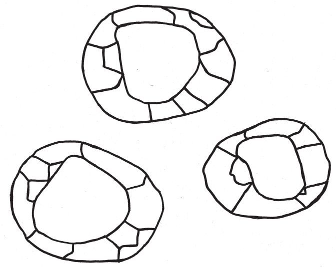


Figure 17: The Delvo®crete Stabilizer, when dispersed and thoroughly mixed into a freshly batched concrete mix, stops cement hydration by forming a protective barrier around the cementitious particles.

The Delvo®crete Stabilizer functions in a dual role by stopping cement hydration by forming a protective barrier around cementitious and pozzolanic particles and acting as a dispersant, thus preventing hydrates from flocculating and setting.

The stability provided by the Delvo®crete Stabilizer is such that even returned concrete may be stabilized and kept in plastic for a few minutes, several hours, overnight or even over a weekend.

The Delvo®crete Stabilizer is composed of carboxylic acids and phosphorous containing organic acids and salts. It is capable of retarding all cement minerals and reduces the rate of calcium sulphate mineral solution. Its action is different to that of conventional retarding admixtures which, at normal dosages, is complex and can accelerate one mineral component of the cement, whilst retarding others. At higher dosage rates, conventional retarding admixtures may even cause severe concrete stiffening, flash set and low strength performance. Thus, by using conventional retarding admixtures at dosages high enough to achieve the same degree of retardation as the Delvo®crete Stabilizer, detrimental effects to both the plastic and hardened concrete can occur.

The Delvo®crete Stabilizer, therefore, may be used to control cement hydration for periods of up to 72 hours. It predominantly affects C_3S hydration, but can also delay the initial C_3A reaction with water and sulphate if it is added with the mix water.

Normal setting and hardening characteristics of the concrete may be achieved in two ways. One is to allow the action of the Delvo®crete Stabilizer to wear off. The other is to add Delvo®crete Activator to the concrete to break down the protective barrier surrounding the cement grains (Figure 18).

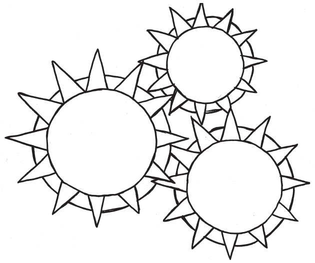


Figure 18: The Delvo®crete Activator, when dispersed and thoroughly mixed into a stabilised sprayed concrete mix, breaks down the protective barrier around the «stabilized» cementitious particles.

As soon as this protective barrier is broken down, the treated concrete will react in the normal way (Figure 19).

Because of the various requirements of setting, high build and early strengths of sprayed concrete for rock support, a range of Delvo®crete Activators are available when the hydration control system is used in this application. These Delvo®crete Activators break down the protective barrier created by the Delvo®crete Stabilizer and then react with the cement to give the fast setting and early strengths normally associated with accelerated sprayed concretes.

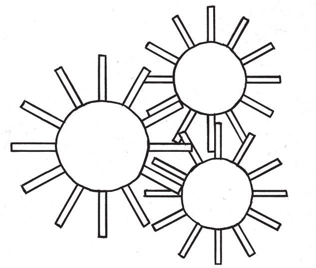


Figure 19: Once the Delvo®crete Activator has broken down the protective barrier surrounding the cementitious particles, normal cement hydration, setting and strength development take place.

4.2.5 Performance

The technical performances of hydration controlled concretes and sprayed concretes treated with the Delvo®crete system exhibit qualities equal or superior to reference concretes manufactured conventionally.

In sprayed concrete applications, hydration controlled mixes have shown improved compressive, tensile and flexural strengths when compared with reference mixes. Kinney observed that the Delvo®crete Stabilizer appears to slow CSH nuclei formation when added with the mix water and slows both CSH and CH when added during or after the induction period. It is suggested that this ability to affect nucleation and crystal growth leads to the formation of finer CH and denser silicate hydrates, resulting in beneficial physical paste properties.

4.2.6 Setting times

The setting times of stabilized and activated sprayed concretes, both wet and dry mixes, are shown in Figure 20.

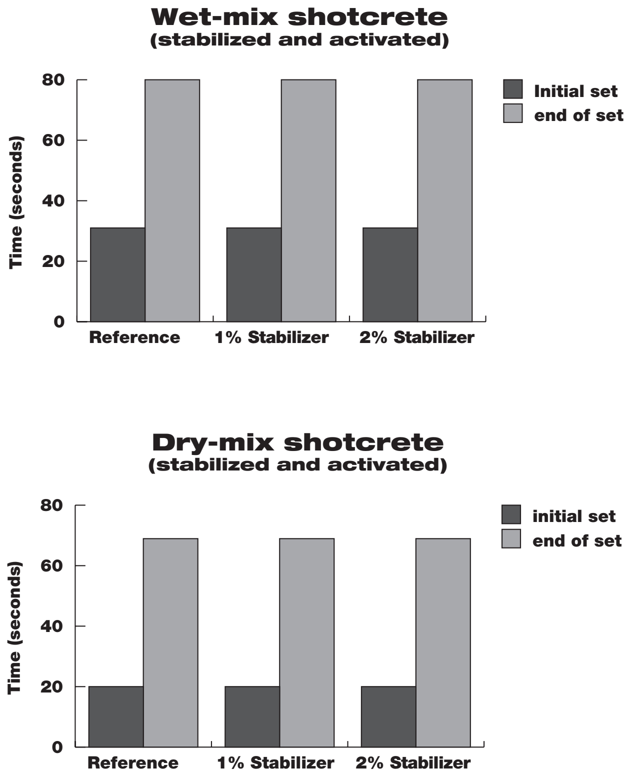


Figure 20: Setting times of hydration controlled sprayed concretes

The Delvo®crete Activators have a dual role in that they:

- Neutralize the effect of the Delvo®crete Stabilizer on the cement, and,
- Accelerate the hydration of the cement to give the very fast setting and high early strength characteristics required in support works.

4.2.7 Strengths

The ultimate strengths and bearing capacity of sprayed concrete for rock support often have to take secondary importance to the requirements for fast setting and high early strength. To achieve the latter characteristics, sprayed concretes have accelerators added to them in the spraying nozzle. These accelerators are mostly based upon salts of aluminates or silicates, and cause «strength losses» at 28 days, the greater strength losses mostly being experienced with aluminates. In reality, strength losses do not generally occur, but rather a lack of strength gain after 3 days takes place, when compared with the same unaccelerated mix as a reference.

With the hydration control system, stabilized and activated sprayed concretes can also exhibit depressed or marginal strength gains between 3 and 28 days similar to conventionally accelerated sprayed concretes. However, there are several types of Delvo®crete Activators for rock support. The choice and dosage of a particular type is dependent upon cement quality as well as early strength and setting time requirements.

It is interesting to note that the hydration controlled mix requires a lower dosage of Delvo®crete Activator than the dosage of accelerator a normal mix would require. This is probably due to the fact that because the cement in the stabilized mix was well dispersed and still «fresh» (i.e. unhydrated), the Delvo®crete Activator is able to act more efficiently than the accelerator used in the normal mix.

4.2.8 Rebound

The rebound of sprayed concrete mixes is a large «add-on» cost in an underground construction project and it is in the interests of the contractor and owner to keep these costs to a minimum. In field tests in Europe and Asia, it has been found hydration controlled sprayed concrete mixes exhibit lower rebound than plain mixes. This is probably due to the fact that in such mixes, no pre-hydration of the cement has taken place and, consequently, «fresh» cement is being sprayed continually, regardless of the time elapsed between batching and spraying.

In the Flurlinger Tunnel project in Switzerland measured rebound tests comparing normal sprayed concrete with a hydration controlled sprayed concrete showed that the rebound of the stabilized mix was up to ten percentage points lower than that of the normal mix.

Sprayed concrete as used in the Flurlinger Tunnel project in Switzerland

Mix design (per m³):	
Cement	425 kg
Aggregate (0–16 mm)	1730 kg
Superplasticizer	0.8 %
Delvo®crete Stabilizer	0.6 %
Delvo®crete Activator S51	5.0 %
w/c ratio	0.45
Workability (DIN Flow Table):	
At batching	600 mm
After 4 hours	580 mm
After 9 hours	560 mm
Compressive strength (28 days):	
Required minimum	25 MPa
Average achieved	33.5 MPa
Measured rebound (robotic spraying):	8 to 10 % (average)

Originally, the contractor started to use stabilized sprayed concrete at night because local environmental legislation restricted the operation of the site installed concrete batching plant to between 7:00 a.m. and 10:00 p.m. This meant that the contractor could not obtain concrete mixes after 10:00 p.m. To overcome this problem, several truck loads of stabilized sprayed concrete were batched into truck mixers before 10:00 p.m. and then driven into the tunnel and sprayed, as required, throughout the night. However, due to the positive experiences in rebound reduction and improved quality and efficiency, the contractor eventually opted to use stabilized concrete mixes in the daytime spraying operations as well, the cost of the hydration control system chemicals being more than offset by the reduction in rebound. This resulted in substantial savings on the project.

4.2.9 Economics

The estimating and costing of the various components relating to the final in-place price of sprayed concrete in a large underground infrastructure project is a difficult and complex task. Many of these costs are overlooked or underestimated by contractors. They may be summarised as follows:

- The cost of the sprayed concrete mix per m^3
- The cost of in-place applied sprayed concrete, allowing for rebound and overspray. (This may be 100 % higher than the delivered m^3 cost.)
- The cost of collecting, loading, carting away and dumping of rebound from a project to a suitable approved site (environmental legislation)
- The cost of returned sprayed concrete that has to be rejected because it is too old to use
- The cost of waste sprayed concrete that has to be washed out of pumps and hoses when breakdowns and delays cause interruption to spraying operations, and at the end of spraying shifts
- The cost of breaking out, removal and replacement of areas of defective sprayed concrete resulting from the application of material that may have been too old
- The cost and maintenance of sprayed concrete pumps and equipment
- The cost and maintenance (per m^3) of a «trixer» unit if being used on a project
- The cost of setting up a site batching plant on the project if the nearest ready-mix concrete plant is too far from site, and the 24-hour operation of the plant
- The cost of down time in equipment and personnel when deliveries of sprayed concrete are delayed, or interrupted

Many of these costs are difficult to quantify and estimate at the tender stage of a project and consequently get overlooked. It may be seen, however, that a reduction in rebound alone has far more cost advantages to a contractor than by merely having to purchase less material.

By utilizing the Delvo®crete hydration control system in large volume wet-mix sprayed concrete projects, cost savings may be made in the following areas:

- Reduction in rebound
- Less rebound to be carted away and dumped
- No sprayed concrete deliveries have to be rejected because they are too old
- Waste sprayed concrete in pumps and hoses does not have to be washed out and disposed of when interruptions occur, nor at the end of a spraying shift
- Less defective in-place sprayed concrete due to the fact that all applied sprayed concrete contains cement that has not undergone any pre-hydration and has not expired its «pot-life»
- The necessity for «trixer» units is eliminated
- Site batching plants may be eliminated (dependent upon other concrete requirements on the project)
- The cost of overtime and down time in plant and personnel may be reduced by ensuring adequate sprayed concrete deliveries are always available at the excavation face

The costs of using the Delvo®crete hydration control system in sprayed concrete can therefore be extremely economical. The dosage of the Delvo®crete Stabilizer is in the range of 0.4 to 2.0 % (b.w.). This will stabilize the cement for between 3-4 hours and 3 days. The dosage of Delvo®crete Stabilizer will obviously depend upon the requirements of the contractor, but, generally, a dosage of 0.6 % by weight of cement is used in most works.

The dosage of Delvo®crete Activators is normally equal to (or slightly less than) the dosage of accelerator that would be required by the same sprayed concrete mix that contains no Delvo®crete Stabilizer.

Table 3 shows the cost comparison of conventional and hydration controlled wet-mix sprayed concretes for rock support with coarse aggregate (0-16 mm). If the conventional mix had 20 % rebound, then the in-place cost of the sprayed concrete would be US$ 121.10/0.8 = US$ 151.38/m^3. In order to make the in-place cost of the hydration controlled sprayed concrete of the same order, then the rebound of that mix should be (1 – 133.86/151.38) X 100 = 11 %. It is not unusual for rebound reductions of this magnitude (40-50%) to be achieved, as was done by the contractor in the Flurlinger Tunnel project.

Table 3:

Material	**Unit cost (US$)**	**Conventional mix**		**Hydration controlled mix**	
Cement	$ 80.00/ton	420 kg	$ 33.60	420 kg	$ 33.60
Silica fume	$ 450.00/ton	40 kg	$ 18.00	40 kg	$ 18.00
Aggregate (0-10)	$ 15.00/ton	1680 kg	$ 25.20	1680 kg	$ 25.20
Water	–	210 kg	–	210 kg	–
Plasticiser	$ 0.70/kg	3 kg	$ 2.10	3 kg	$ 2.10
Super-plasticiser	$ 1.10/kg	4 kg	$ 4.40	3 kg	$ 3.30
Delvo®crete Stabiliser (0.6%)	$ 3.50/kg	–	–	2.76 kg	$ 9.66
Slump	–	200 mm plus		200 mm plus	
Conventional accelerator (5%)	$ 1.80/kg	21 kg	$ 37.80	–	–
Delvo®crete Activator (5%)	$ 2.00/kg	–	–	21 kg	$ 42.00
	TOTAL	US$ 121.10		US$ 133.86	

In the case of higher cost steel fibre reinforced sprayed concrete (which may cost in excess of US$ 200 per m^3), an even smaller reduction in rebound will be required to offset the cost of the hydration control system chemicals.

Apart, however, from rebound savings, the contractor will also make cost savings by eliminating return and waste sprayed concrete, being able to reduce down time of sprayed concrete pumps and personnel and generally being assured that every cubic metre of sprayed concrete applied will be of a consistent quality.

4.2.10 Summary

- Hydration controlled sprayed concrete mixes are an economical and efficient development for use in rock support for large underground infrastructure projects.

- By suspending the hydration of the cement (and pozzolans) in a sprayed concrete mix until it is reactivated and accelerated at the spraying nozzle, a consistent quality of applied sprayed concrete may be assured.
- Cost savings in rebound reduction alone can offset the additional costs of the hydration control system.
- Other cost savings, resulting from reduced rebound and eliminating waste sprayed concrete may be achieved by contractors.
- Hydration controlled sprayed concrete mixes enable greater flexibility in the scheduling and programming of spraying operations in underground construction projects.

4.2.11 Selected case studies

The flexibility and advantages of modern high performance wet-mix SFRS is directly and tightly lined to the correct use of admixtures and proper equipment. Some examples follow, where a selection of features has been made, to demonstrate some of the more important aspects of practical life sprayed concrete application.

A) Wet-mix spraying with Delvo®crete

Athens Metro

The civil construction part of the project comprises 20 stations and 18 km of tunnels. In the tender documents, the dry-mix method was specified. It was, however, possible to convince the contractors that wet-mix spraying is beneficial in all aspects and the method is now being used.

From a central mixing plant, the concrete is distributed by truck mixers to a number of sites. The individual sites have a buffer storage for concrete, holding about 12 m^3 maximum. The buffer is also an agitator that can be operated when necessary. The concrete goes from the agitator into a concrete pump, delivering through a pipe system down the shaft (typically 20 m deep) into the tunnel, ending in the MEYCO® Suprema spraying pump. To the spraying nozzle it is normally 100 to 150 m.

A normal work sequence means application of 3 to 4 m^3 of sprayed concrete and then a full stop of 3 to 4 hours until the next application. During this time, the whole system from day-buffer to the sprayed concrete nozzle is left untouched with concrete inside. A full cleaning of the delivery system is carried out about once a week.

This logistics system is only possible due to the Delvo®crete Stabilizer. By adding a maximum of 2 % drawn on the cement weight, it is possible to prevent any hydration for up to 72 hours. When Delvo®crete is used for sprayed concrete, an activator must be used in the nozzle to start the hydration process.

Some key data of the sprayed concrete:

- Mix design containing 400 kg of cement, aggregate 0–8 mm, Rheobuild® 716 superplasticizer (1.2 %), Delvo®crete Stabilizer (1 %), w/c ratio <0.45, slump 18-20 cm at the batching plant and Delvo®crete Activator S71 (5–6 %) added at the spraying nozzle.
- This is producing a rebound rate <10 %, early strength development better than the class J3 according to the Austrian Sprayed Concrete Norm, 24-hour strength of 13–17 MPa and 28-day strength of 30 MPa.

London Underground, Jubilee Line Section 102

From a mixing plant on surface, the concrete is dropped about 35 m down a vertical shaft, from where it is transported in 4 m^3 re-mix trucks. The trucks deliver it into the MEYCO® Suprema concrete pump, which is located from 45 to 100 m behind the nozzle, depending on advance during the week.

A normal work sequence means application of 4 to 5 m^3 of sprayed concrete and then a break of 2 to 3 hours until the next application. Meanwhile, the equipment is cleaned once a week or occasionally if blockage occurs. The about 5 m diameter tunnel in London clay is advanced about 30 m/week on five 24-hour days.

Some key data of the sprayed concrete:

- Mix design containing 440 kg of cement, aggregate 0–10 mm, Rheobuild® 3520 superplasticizer (1.15 %), Delvo®crete Stabilizer (0.9 %), slump 20 cm at the batching plant and 13 cm underground (flow measure according to DIN is more relevant using this superplasticizer) and Delvo®crete Activator S51 (4–5 %) added at the nozzle.
- This is producing a rebound rate of 5 %, a 24-hour strength of 20–24 MPa and 28-day strength of 30 MPa.

It is interesting to note that Delvo®crete was not used at the beginning. This caused a loss of about 2 m^3 of concrete for every 4 m^3 sprayed, due to cleaning out of equipment between application phases.

Bianya Tunnel, Spain

The Bianya Tunnel with a length of 1'800 metres is part of the Andorra Highway to France. Contractor is Dragados y Construcciones. The isolated area shows several impediments to conventional tunnelling operations. The nearest ready-mix plant is 25 km away from the job site and can only be reached across an ancient mountain pass. More than 1.5 hours are needed to reach the Northern end, and 50 minutes to reach the Southern end of the tunnel.

During a period of 20 months, continuous night and day shifts require guaranteed non-stop supply of 15'000 cubic metres of sprayed concrete mixes, also under severe weather conditions, for the use in rock support.

With the Delvo®crete system the sprayed concrete mixes are stabilized at the batching plant for an average of 14 hours. They are delivered to the job site and stored until utilisation. This allows continuous availability of fresh mixes.

Some key data of the sprayed concrete:

• Concrete properties:		
– Initial slump	23 cm	
– Slump after 14 hours	19 cm	
– Compressive strength	1 day:	9 MPa
	3 days:	18 MPa
	7 days:	27 MPa
	28 days:	40 MPa
• Rebound:	<6 %	
• Output:	9 m^3/hour	
• Mix design (per m^3):		
Cement	500 kg	
Microsilica	16 kg	
Sand (0–1 mm)	150 kg	
Sand (0–6 mm)	1400 kg	
Gravel (6–12 mm)	20 kg	
Rheobuild® 561	5 kg	
Delvo®crete Stabilizer	3–5 kg	
Dramix steel fibres	40 kg	
Water	225 kg	
Delvo®crete Activator S61	30 kg	

A-14 Highway, Paris

A twin road tunnel of 1’700 m was driven with the Perforex system underneath the city of Paris. Perforex is the name of the equipment for a new tunnelling method that consists in continuous saw cutting of vaults on the extrados of the tunnel. The voids are immediately filled with high early strength sprayed concrete, thus building a preliminary shelter before the actual excavation works (e.g. road header) start. This new technique is specially suited for full face driving in unstable and loose areas below densely populated zones. Perforex requires simple and reliable materials that are easy to handle and to place and can be adapted to non-anticipated situations.

Some key data of the sprayed concrete:

- The Stabilizer of the Delvo®crete system provided the required flexibility of sprayed concrete placing.
- The Activator of the Delvo®crete system provided the required high early strength; at 4 hours an average of 11–13 MPa was reached instead of the required 6 MPa; at 7 hours 17 MPa were reached.
- Reduced production time: overall tunnelling works proceeded faster.
- Mix design (per m^3):

Cement	425 kg	
Aggregate (0–8 mm)	1’660 kg	
Water	190 litres	
Rheobuild® 2000 PF	1 %	(c.w.)
Delvo®crete Stabilizer	0.4 %	(c.w.)
Delvo®crete Activator S71	5 %	(c.w.)

Ditschardt Tunnel, Germany

The Dischardt Tunnel is part of the by-pass road around the city of Altenahr, 40 km south of Bonn. The tunnel length is 565 m and the excavated cross section is 145 m^2. The tunnel was excavated by drill and blast and supported by sprayed concrete, rock bolts, welded wire fabric and arches, according to the principles of NATM. The tunnel alignment passed heavily jointed graywacke which partly caused substantial overbreaks. The concrete mix needed for wet-mix spraying had to be hauled from a ready-mix plant 25 min off the jobsite. Variable timing of tunnelling activities created additional waiting times.

Some key data of the sprayed concrete:

- The Stabilizer of the Delvo®crete system provided the required flexibility of sprayed concrete placing, without quality loss. The concrete delivered to the site was kept in a site truck mixer until the moment of application. A plasticizer was added to bring the spread table flow measure up to 50 cm.
- Mix design (per m^3):

Cement CEM I 32.5R	380 kg	
Sand (0–2 mm)	880 kg	
Aggregate (2–8 mm)	980 kg	
Water	200 kg	
Woerment FM21 (plasticizer)	0.5%	(c.w.)
Delvo®crete Stabilizer	0.8%	(c.w.)
Delvo®crete Activator	6.1%	(c.w.)

- The Delvo®crete hydration system was equally reliable during the cold winter of 95/96 and during summer.

B) Dry-mix spraying with Delvo®crete

Brighton & Hove Stormwater Relief Tunnel, UK

The Brighton & Hove Stormwater Relief Tunnel was driven along the foreshore, 30–40 m beneath the surface, between Brighton and Hove on the South-East coast of the United Kingdom. The main tunnel is 5.3 km long with an excavated diameter of 6 m, and was to be bored by a full-face TBM. Lining was by pre-cast concrete segments.

The main shaft combines pre-cast concrete with a sprayed concrete section for TBM erection and spoil handling, built in accordance with NATM design criteria. Due to the environmental requirements of the area – a famous year round bathing and pleasure resort – the erection of a ready-mix concrete plant had to be avoided and the concrete mixes required to be sprayed at various times throughout the day, had to be hauled 12 km.

To ensure a regular supply of quality sprayed concrete, the Delvo® crete system was chosen by Taylor Woodrow Civil Engineering, the main contractor. The dry-mix sprayed concrete, stabilized with Delvo®crete Stabilizer, was applied via two MEYCO® GM 90’s and, due to the wet conditions in the shaft and tunnel, activated/accelerated with Delvo®crete Activator S51. Concrete some 15 hours old had been sprayed with excellent results.

4.3 Concrete improving (internal curing)

Tunnels and other underground construction projects have some of the worst conditions for curing due to the ventilation that blows continuously dry (cold or hot) air into the tunnel. It can be compared with concrete exposed to a windy area. One would think that tunnels have ideal curing conditions with high humidity (water leakage), no wind and no sun exposure. However, this is not the case.

4.3.1 Background

Curing is one of the basic and most important jobs in sprayed concrete because of the large cement and water content of the mix and the consequent high shrinkage and cracking potential of the applied concrete. Another reason is the danger of rapid drying out due to the heavy ventilation as is usual in tunnels, the fast hydration of accelerated sprayed concrete and the application in thin layers. Therefore, sprayed concrete should always be cured properly by means of an efficient curing agent. However, the use of curing agents involves several restrictions: They must be solvent-free (use in closed rooms), they must have no negative influence on the bonding between layers and they must be applied immediately after placing of the sprayed concrete. Most of the in-place sprayed concrete around the world has no bonding and many cracks, due to the fact that no curing is applied.

With the use of sprayed concrete as permanent final lining, long-term quality and performance requirements have built up significantly. These requirements are: good bonding, high final density and compressive strengths to ensure freeze/thaw and chemical resistances, watertightness and a high degree of safety.

When curing sprayed concrete with a curing agent, one has to be very careful with the cleaning procedure of the substrate before applying a subsequent layer. Cleaning must be done with high pressure air and a lot of water (use spraying pump and nozzle, adding air at the nozzle). Another problem with curing agents is to be able to apply them quickly enough after finishing of spraying. To secure proper curing of sprayed concrete, the curing agents must be applied within 15 to 20 minutes after spraying. Due to the use of set accelerators, the hydration of sprayed concrete takes place a very short time after spraying (5 to 15 minutes). The hydration and temperature are most lively during the first minutes and hours after the application of the sprayed concrete and it is of great importance to protect the sprayed concrete at this critical stage.

Application of curing agents requires two time consuming working operations: Application of curing agent and cleaning/removal of the curing agent from the sprayed concrete surface between the layers in the case of multiple layers. In many countries with experience in wet-mix sprayed concrete like in Norway and Sweden and in big projects world-wide, there is an obligation to cure the sprayed concrete with a curing agent.

Very good experiences have been made with the use of a special curing agent for sprayed concrete (Masterkure® 112). This product is solvent-free and easy to apply and remove. It is used in many big projects and in different countries, everywhere with very good results. The use of specially designed curing agents for sprayed concrete improves bonding by 30–40 % compared to no curing (air curing), reduces shrinkage and cracking and also gives a slightly higher density and compressive strength (at 28 days). These results are confirmed by several laboratory tests and field trials. However, in order to achieve these results, proper cleaning is required before subsequent layers of sprayed concrete can be applied. Even with easy-to-apply products, curing of sprayed concrete remains a time consuming job and is often felt as a hindrance to other tunnelling operations.

4.3.2 Concrete improving with MEYCO® TCC735

MBT has developed a new system for more efficient and secure curing of wet-mix sprayed concrete, repair mortars as well as concrete.

Concrete improving (internal curing) means that a special admixture is added to the concrete/mortar during batching as a normal admixture. This admixture produces an internal barrier in the concrete which secures safer hydration and better resistances than the application of conventional curing agents.

The benefits resulting from this new technology are impressive:
- The time consuming application and, in the case of various sprayed concrete layers, removal of curing agents are no longer necessary
- Curing is guaranteed from the very beginning of hydration
- There is no negative influence on bonding between layers

As a consequence of this optimum curing effect, all other sprayed concrete characteristics are improved: density, final strengths, freeze/thaw and chemical resistances, watertightness, less cracking and shrinkage.

In addition, MEYCO® TCC735 also improves pumpability and workability of sprayed concrete, even with low-grade aggregates. It particularly improves the pumpability of steel fibre reinforced sprayed concrete mixes. In combination with the MEYCO® TCC system it contrives to even increase the beneficial effects of the slump killing system by further improving fibre orientation, reducing fibre rebound and thus raising toughness values.

4.3.3 A proven technology

The concrete improving system with MEYCO® TCC735 has been tested with good results both in laboratories and on big jobsites. Comprehensive investigation programmes were carried out in Norway (SINTEF), in Switzerland (LPM Institute) and in Austria (University of Innsbruck). Bond strengths were higher than 2.0 MPa with failures discovered in the concrete only and not in the bonding area. Density and mechanical strengths at 28 days were more than 10% higher than in conventionally cured reference sprayed concrete.

Example results from a large jobsite in Middle East:
- Increased bonding compared to no curing: >100 % (from 0.5–0.7 to >2.0 MPa)
- Increased bonding compared to curing with special curing agent: >30–50 % (from 0.7–1.2 to >2.0 MPa)
- All cores of sprayed concrete treated with MEYCO® TCC735 show bond >2.0 MPa. Failures were discovered only in the concrete and not in the bonding area.
- Increased density (>15 %) compared to sprayed concrete treated with external curing agents
- Increased strength (28 days) compared to air cured sprayed concrete or treated with external curing agent (>10 %)
- No signs of cracking

4.3.4 Benefits of concrete improving with MEYCO® TCC735

- No influence on bonding between the layers. Always good bonding, high security
- No additional work operation for the application of curing agents or other curing methods
- No need for additional work operation for cleaning and removal of curing agents
- Curing from the first second and therefore during the critical time
- Less cracking
- Better chemical resistance
- Improved watertightness (less cracks)
- Improved freeze/thaw resistance
- Improved workability and especially pumpability
- Works independently from aggregate quality, grading and lack of fineness
- Works particularly well with steel fibre reinforced sprayed concrete; better fibre orientation, reduced fibre rebound and increased toughness values
- Less time per m^3/m^2 due to increased production and less work operations. Time is money!
- Increased density
- Improved final compressive strengths

4.3.5 A safer and cheaper solution

- With MEYCO® TCC735 overall savings of the spraying job are achieved: the elimination of additional work operations for application of curing compounds and preparation of substrate, as well as the reduced rebound and fibre rebound more than offset the extra material cost.
- MEYCO® TCC735, whilst guaranteeing safer curing, provides a new state of the art application procedure of curing agents in the easy-to-apply form of a concrete admixture.

Table 4: Cost comparison per m³ of concrete improver, external curing and water curing from one of the biggest sprayed concrete works ever carried out: >200’000 m³ of wet HPS sprayed concrete applied in a period of 2.5 years

	Water curing	**External curing**	**Concrete improver (internal curing)**
Material	–	SFr. 14.–	SFr. 15.–
Application			
man hours	SFr. 25.20	SFr. 1.–	–
machine costs	SFr. 280.–	SFr. 18.–	–
Removal			
man hours	–	SFr. 10.80	–
machine costs	–	SFr 80.–	–
Total costs m³	**SFr. 305.20**	**SFr. 123.80**	**SFr. 15.–**

4.3.6 Results from some spraying tests

In the tests a great number of parameters have been fixed in order to evaluate the real performance differences of the three mixes and systems.

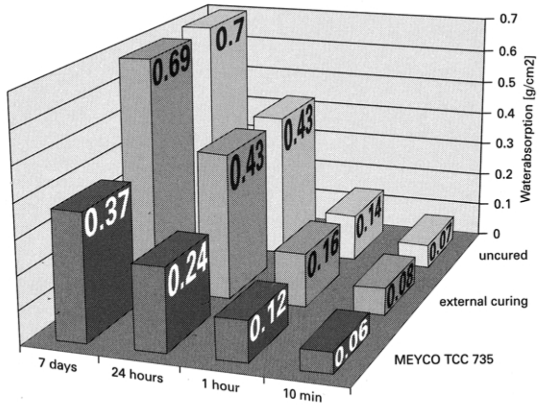


Figure 21: Water absorption of a drilling core [g/cm²]
(Ref: M. Testor, Master’s degree at the University of Innsbruck, 1997)

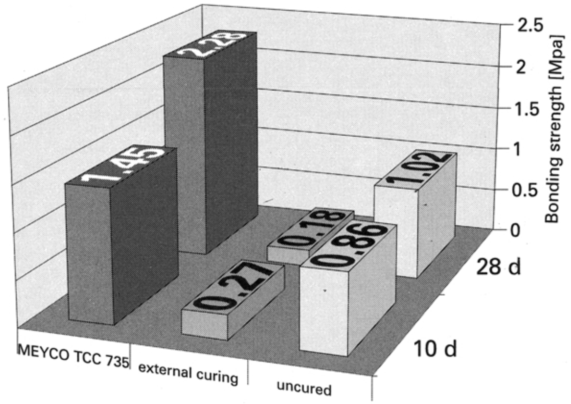


Figure 22: Bonding of sprayed concrete drilling cores on sprayed concrete substrate [MPa]
(Ref: LPM test results from internal spraying trials)

Table 5: Mix design per m³

	Reference (no curing)	**External curing**	**Concrete improver (internal curing)**
Cement 42,5 II A-L (c)	450 kg	450 kg	450 kg
Silica fume (s)	22.5 kg	22.5 kg	22.5 kg
w/c+s	0.45	0.45	0.45
Sand 0-4 mm	1’700 kg	1’700 kg	1’700 kg
Rheobuild® 561	7.125 kg	7.125 kg	–
Masterkure® 112	–	0.5 kg/m²	–
Rheobuild® 3520	–	–	9.5 kg
MEYCO® TCC735	–	–	5 kg
Rheobuild® 700	–	–	1 kg
MEYCO® SA430 (by b.w.)	8 %	8 %	–
MEYCO® TCC765 (by b.w.)	–	–	5 %
Slump	23 cm	23 cm	16 cm

Table 6: Mechanical performances of the three mixes

	Reference (no curing)	**External curing**	**Concrete improver (internal curing)**
Flexural strength tests on concrete beams (10 x 10 x 40 cm), UNI 5133, MPa:			
7 days	**3.8**	–	5.9–6.1 **6.0**
28 days	5.5–4.5 **5**	4.5–4.5 **4.5**	6.4–6.8 **6.6**
Pull-out test Rilem/CEB/FIP RC6, MPa:			
7 days	–	–	2.1–1.9 **2.0**
28 days	**1.5**	2.0–1.8 **1.9**	2.4–2.2 **2.3**
Adhesion on concrete (*), MPa:			
7 days	0.92 (P)	0.9 (P)	1.5 (P)
28 days	1.02 (I)	1.5 (I)	2.8 (P)
Cracks on beams:			
1 day	cracks	no cracks	no cracks
7 days	cracks	no cracks	no cracks
14 days	breakings	superficial cracks	no cracks
28 days	breakings	cracks	no cracks
Static modulus of elasticity, UNI 6556, MPa:			
7 days	17150	–	19100
28 days	21650	–	22400
Dynamic modulus of elasticity, MPa:			
7 days	28500	28000	39400
28 days	36600	37300	39600

(*): The values are the average of two tests.
P: The breakings have occurred in the application, i.e. in the product.
I: The breakings have occurred at the interface between the application and the concrete slab.

4.4 Conclusion

Delvo®crete, the alkali-free set accelerators MEYCO® SA160/SA161/SA162/SA170 and the concrete improving system are the new generations of advanced sprayed concrete admixtures which set new standards in the world of sprayed concrete. They contribute to improve quality and increase production, while at the same time lowering costs per cubic metre of in-place sprayed concrete and thus further promoting sprayed concrete as a construction material.

5. Fibres in sprayed concrete

Fibre concrete is a new material undergoing fast development with new and better fibres, hand in hand with improved concrete technology and application techniques.

Figure 23: Steel fibres as used for reinforcing of sprayed concrete for rock support

The use of steel fibre reinforced sprayed concrete has advanced substantially in the last few years. It has been accepted for rock support by engineers, specifiers, owners and contractors around the world.

5.1 Why concrete needs reinforcement

Concrete is a brittle material. For a variety of reasons most of all applied concrete and sprayed concrete cracks. The cause of concrete cracks can be structural or economical, but most of the cracks are due to the inherent tensile weakness of the material. As concrete shrinks, and at the same time is restrained, it will crack. To avoid this the concrete has to be reinforced with wire mesh and bars, or by adding fibres.

Steel fibres have clear advantages over wire mesh as reinforcing agents. The most important advantage is that they are small and that steel fibres are evenly distributed in the entire concrete layer. The improved distribution of cracks and tension thus obtained makes steel fibre reinforced concrete a viscous material.

5.2 How steel fibres work in sprayed concrete

To a large extent the mechanical properties of sprayed concrete are determined by the w/c+s ratio, the silica fume content, the dosage of sprayed concrete accelerators and the curing conditions.

The main reason for using steel fibres in sprayed concrete is to increase the ductility of the material. Whereas high flexural strength can be produced without fibres, ductility is a function of the type and amount of steel fibres. Long fibres (>25 mm) and rather high dosages (40–75 kg/m^3) are preferable.

As a secondary effect steel fibres improve the final flexural strength of sprayed concrete. Tests on large scale specimens show that after hardening the flexural strength of plain sprayed concrete was reduced by half because of shrinkage and microcracking whereas steel fibre reinforced sprayed concrete maintained its flexural strength.

Additional benefits obtained by using steel fibres in sprayed concrete are:

- Increased resistance against impact
- Increased abrasion and erosion resistance
- Increased watertightness and frost resistance due to the conversion of shrinkage cracks into microcracks
- Increased bonding capacity as compared to plain or wire mesh reinforced sprayed concrete

Steel fibres should never be used in dry-mix spraying because of the high fibre rebound (>50%).

5.3 Types of fibres

5.3.1 Glass fibres

Glass fibres cannot be used as a permanent material because, after some time, they will become brittle and be destroyed by the basic part of the concrete matrix. Therefore, they have to be avoided in all types of concrete, sprayed concrete and cement based mortars.

5.3.2 Plastic fibres

Normal short plastic fibres are resistant and durable in the concrete environment. Yet, their mechanical properties are similar to those of concrete and therefore cannot improve them or make concrete more viscous. This makes these plastic fibres unsuitable for the use in rock support. However, for applications where only reinforcement against shrinkage, and in particular plastic shrinkage, is asked for, as in sprayed concrete repair, plastic fibres are well suited: They are very efficient at distributing microcracks during the plastic phase of hardening and they also help reduce rebound in wet-mix spraying. In addition, plastic fibres have a positive influence on the fire resistance of sprayed concrete.

Recently, developments in the US (Synthetic Industries) have come up with a new type of plastic fibre which is more similar to a steel fibre in terms of shape. The so called new HPP 152 plastic fibres are made of high quality materials and are delivered in a length of 30 and 50 mm. Different test results from Australia and Europe show that this type of fibre can reach a suitable toughness if moderately dosed (10-13 kg/m^3). The tests also show that HPP 152 fibres reach about 700-900 Joules according to the EFNARC plate test. This result is more or less equal to the result achieved with 30 – 40 kg/m^3 of high quality steel fibres. This new plastic fibre type is of interest for the industry and can be an important addition to sprayed concrete where steel fibres cannot be used for various reasons (e.g. surface correction, fibres in the surface and where efficient reinforcement is required to improve the ductility of sprayed concrete).

One of the main problems we still face with the new HPP 152 fibres is the high fibre loss. The mix design has to be altered in order to produce a higher spread and a new spraying technique has to be used (different pattern, shorter distance to the substrate and less air). It could be interesting to combine a low dosage of the new HPP 152 fibres with steel fibres in order to obtain excellent ductility, less cracks, low rebound and cost savings due to the lower fibre content per m^3.

Table 7: Results from a comparison test made with Harex Steel Fibres (various dosages) and HPP 30 and 50 mm (various dosages) in Moab, South Africa. As a conclusion from this test it can be stated that 7.5 kg/m^3 of HPP 50 provide a higher energy absorption than 40 kg/m^3 of the tested steel fibres.

Fibre type and content	Panel thickness (mm)	Energy absorption Individual results	Average
20 HX, 20 kg	A: 107 B: 114 C: 113	194 206 232	211
30 HX, 30 kg	A: 117 B: 113 C: 132	519 285 341	382
40 HX, 40 kg	A: 99 B: 108	288 370	329
5 HPP, 5 kg (30 mm)	A: 110 B: 106 C: 108	224 243 142	203
7.5 HPP, 7.5 kg (30 mm)	A: 92 B: 108 C: 102	136 212 102	150
10 HPP, 10 kg (30 mm)	A: 112 B: 108 C: 114	371 393 230	331
5 HPP, 5 kg (50 mm)	A: 106 B: 100 C: 99	249 146 176	190
7.5 HPP, 7.5 kg (50 mm)	A: 104 B: 100 C: 113	539 35* 394	467
10 HPP, 10 kg (50 mm)	A: 107 B: 125 C: 121	527 865 558	650
28 HX & 5 HPP 20 kg HX + 5 kg HPP 50 mm	A: 111 B: 124 C: 132	413 401 497	437

*: Panel visually cracked - result not included in average calculations

HX: Harex steel fibres, 1100 MPa steel quality

5.3.3 Carbon fibres

From a technical point of view the mechanical properties of carbon fibres should be ideal for rock support, but in practice they are not used because of their high price.

5.3.4 Steel fibres

Steel fibres are the most commonly used fibres in sprayed concrete. There are several types and qualities available on the market, but only a few types meet the requirements set for fibre reinforced sprayed concrete.

Critical and important parameters of the steel fibres are:
- Geometry
- Length
- Length/thickness ratio (L/D)
- Steel quality

In practice, we are looking for a thin and long fibre with high steel quality (same or higher than ordinary reinforcement). Most of the steel fibres available on the market have an insufficient steel quality. Typical fibres that can meet the requirements for steel fibre reinforced sprayed concrete are Dramix 30/50 and 40/50, Novotex 0730 (0.7 x 30 mm) and Harex CF 30/0.5.

5.4 Technical advantages of steel fibres

Rock support includes the constant risk of unexpected loads and deformation. The best possible safety margin is achieved by the highest possible fracture energy (ductility) of the sprayed concrete layer.

Whereas the addition of ordinary steel fibres doubles the fracture energy of unreinforced sprayed concrete, modern steel fibre technology improves it 50–200 times, see Figure 24. In practical terms this means that with modern steel fibre technology a sprayed concrete layer may crack and deform and still have a lot of bearing capacity left, so that under normal circumstances there is ample time that the cracks/deformations are noticed and measures taken.

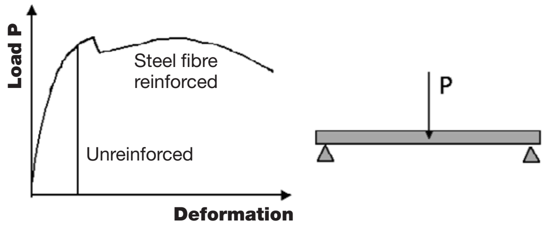


Figure 24: The 2 curves show the deformation under variation of the load P of an unreinforced sprayed concrete layer and a sprayed concrete layer reinforced according to modern steel fibre technology. The area below the curve is the fracture energy.

The fracture energy of steel fibres is also higher than of wire mesh. This has been proven by a large scale test run at the beginning of the eighties by the independent Norwegian Technical Research Association (NTNF), see Figure 25.

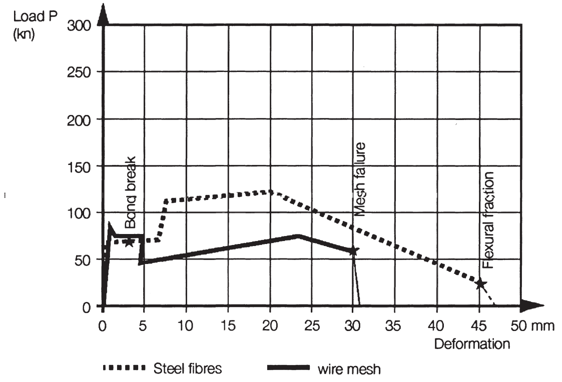


Figure 25: Fracture energy of steel fibres vs. wire mesh.

The test simulates a block falling on a 10 cm sprayed concrete layer.

a) Sprayed concrete with 1% steel fibres
b) Sprayed concrete with centric applied wire mesh

Both types of reinforced sprayed concrete layers were applied with a 10 cm thickness on three granite stone blocks (see Figure 26). After 28 days the middle block was exposed to various loads (P). The resulting deformation was measured.

The test shows that the fracture energy of the steel fibre reinforced sprayed concrete is much higher than that of traditional wire mesh reinforced sprayed concrete.

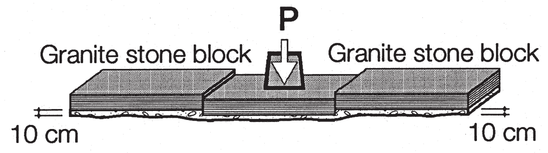


Figure 26

Theoretically, wire mesh reinforced sprayed concrete may produce similar results if the layer thickness is above 15 cm and the steel quality is good. However, commonly used wire mesh is produced from cold drawn wire. This mesh will break already under very small deformation and is therefore dangerous since in rock support deformation has to be taken into consideration constantly.

Reinforcing sprayed concrete by WWF also creates a quality problem. The shadow effect may produce voids behind the bars. This is often a serious problem, because it will eventually cause reinforcement corrosion and concrete spalling.

The danger arising from the insecurity about the wire mesh quality actually used and the problem of the shadow effect can be easily avoided by using steel fibre reinforcement which lends itself so well to wet-mix sprayed concrete, and at a lower cost, too. In rock support where one always has to allow for deformation, this feature is a very strong quality asset of the wet-mix method.

5.5 Economical advantages of steel fibres

By replacing welded wire mesh with steel fibres a time-consuming and dangerous operation can be avoided. This makes fibre concrete able to compete with traditional wire mesh.

Steel fibres save money and time:

- Savings on direct costs:
  Direct cost of steel fibres is 50 to 60 % of the direct cost of wire mesh (labour plus material).

- Savings on indirect costs:
  Indirect costs due to the application of sprayed concrete in two layers which the use of wire mesh makes necessary, can be avoided, and no delay is caused in other tunnelling operations.
- Savings on sprayed concrete used:
  With steel fibres the required thickness of sprayed concrete can be applied over the whole surface, independent of the irregularity of the substrate.
  The increased rebound caused by wire mesh as well as the effect of «shadows» behind the mesh are avoided.

5.6 Mix design for steel fibre reinforced sprayed concrete

Steel fibres require the knowledge and skill of practical mix design.

- Fibre reinforced sprayed concrete requires the use of microsilica and admixtures, in order to cancel the negative effects of the fibres on pumping and spraying. Furthermore, it is important that the bonding (adherence) between steel and concrete matrix is optimal, and this is achieved by the addition of microsilica and with a maximum aggregate grain size of 8 mm.

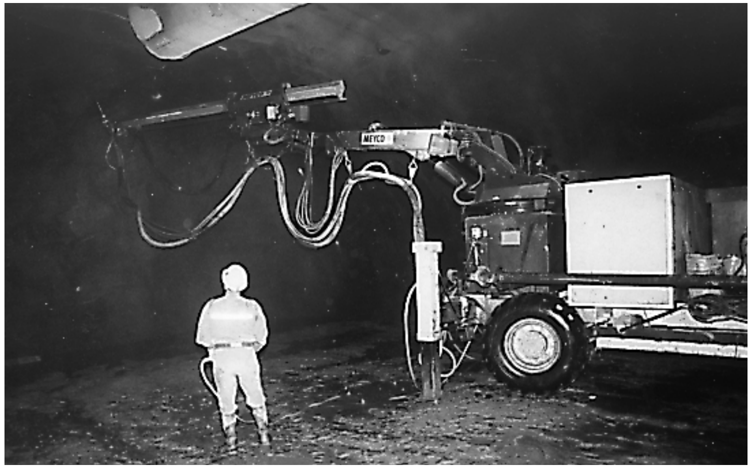


Figure 27: Modern sprayed concrete: Robotic spraying with advanced admixtures and steel fibres

- A higher content of fine material (min. 400 kg) is required.
- The slump has to be increased to a minimum of 10-14 cm. This means that fibre reinforced sprayed concrete requires a higher dosage of superplasticizers.
- For anchoring (gluing) reasons the fibres should be at least twice as large as the largest aggregate granule.
- The fibre length should not exceed 50 to 60 % of the pumping hose diameter. This means that for manual spraying the normal maximum fibre length is 25 mm and for robots with 65 mm hoses, it is possible to spray with a fibre length of up to 40 mm.
- Steel fibres can be added before, after or during batching of the concrete materials. If balling occurs, it is usually eliminated by altering the batching sequence.

6. Durability of sprayed concrete

As a consequence of the growing application of sprayed concrete as a permanent construction material, demands on its durability have increased likewise. The use of traditional accelerators in high dosages has led to serious damages of sprayed concrete, even within a short time after its application.

The durability of a tunnel lining should be such that the lining remains safe and serviceable for the designed life, without the need for a high degree of maintenance expenditure. To attain durability, the designer needs to assess the exposure environment of the structure during both construction and operation, as structural degradation normally occurs with unforeseen environmental changes.

With this in mind, the term «durability» may be related to structures that are designed to resist loads during a construction period before a secondary lining is placed. However, more often, with the use of sprayed concrete for permanent single shell linings (see chap. **9**), the durability of the concrete should consider a design life of 100 years or more.

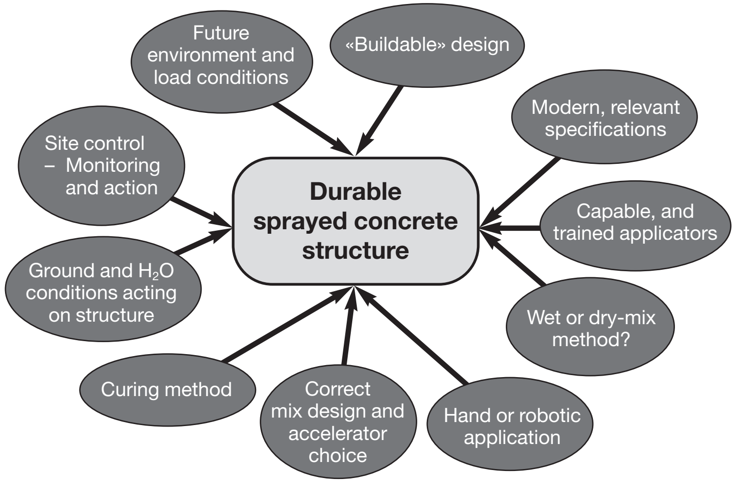


Figure 28: Durability parameters of a sprayed concrete structure

As can be seen from Figure 28, the durability of a sprayed concrete structure is established via a total of many possible parameters. In sprayed concrete construction, the correct concrete mix design and cover to reinforcement are not sufficient as with traditional cast concrete. The main reason behind this is that the material is spray applied, and consequently the quality is significantly reliant on human skills and spray equipment performance. The main durability issues listed in Figure 28 are briefly discussed in this chapter.

6.1 Buildable designs

With respect to existing concrete tunnel structures, the major durability problems are not directly related to the concrete itself, but more often to the corrosion of steel reinforcement elements that have been insufficiently protected against water ingress or humidity. Tunnels constructed with permanent sprayed concrete create other durability concerns, particularly in terms of providing the required material properties such as compaction, and with the unknown stability concerns associated with the necessary amount of admixtures used for modern wet-mix sprayed concrete application methods.

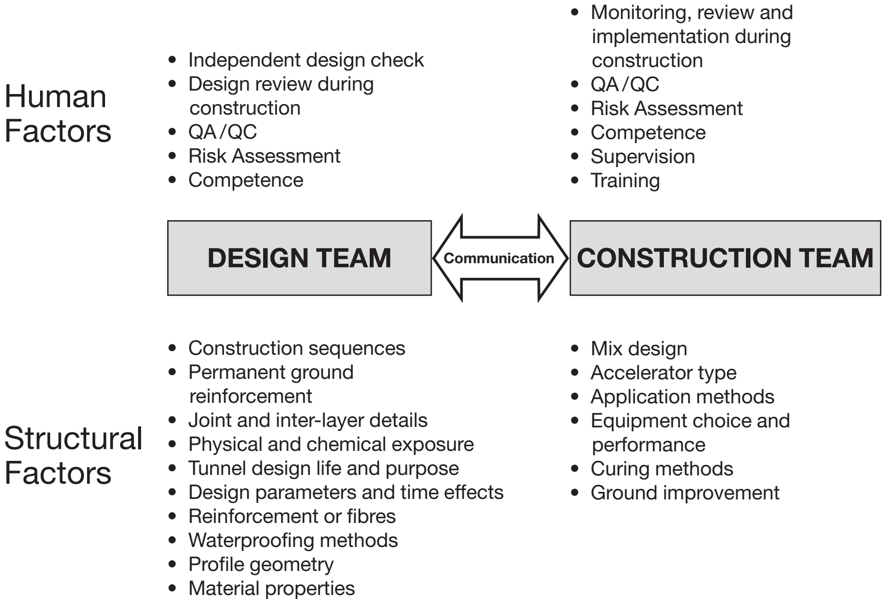


Figure 29: Human and structural factors

As summarised in Figure 29, to address the durability requirements, a holistic approach to the design and construction of durable sprayed concrete tunnel linings is required. In essence, the sprayed concrete lining method is heavily reliant on human competence during construction, and therefore the design should reflect this by considering the «buildability» of tunnels using sprayed concrete.

6.2 Specifications and guidance

Unfortunately, too often in the sprayed concrete industry, specifications and guidance documents tend to be «cut and pasted» into new contracts year after year, without much in depth research as to the current advanced state of the sprayed concrete business. The recent increase in wet-mix sprayed concrete has provided an opportunity to re-examine the «old» specifications, and now new documents are emerging which reflect the current state-of-the-art in sprayed concrete technology (e.g. the European Specification for Sprayed Concrete (1996) by EFNARC, see chap. **10.5**).

6.3 Construction competence

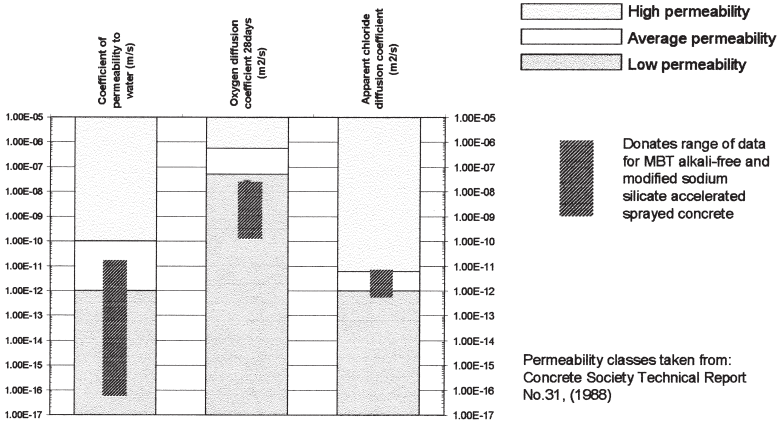
The construction team should be made aware of the design elements that are key factors in determining the safety and durability of the tunnel structure. To ensure the quality of the concrete lining is achieved, quality review systems should be adequate to control the production. It is of paramount importance that the communication link between design and construction teams should be maintained from pre-design stage to project completion so that the above processes are promoted (see chap. **10.5** for more details).

6.4 Sprayed concrete mix design

The main factor that determines the durability of a concrete structure is achieving a low permeability which reduces the ingress of potentially deleterious substances, thereby inhibiting chemical reactions such as those involving the cement and thus preventing chemical changes. Low permeability is achieved in sprayed concrete applications by the following means:

- A well graded material suitable for the sprayed concrete application system in terms of pumpability, workability, rebound reduc-

tion and good compaction (see Figure 5 in chap. **3.5.2**). All aggregates should be checked for alkali-silica reaction.
- Adequate cementitious content, typically 400 to 500 kg. The cement content should not be less than 350 kg.
- Low, pre-defined water/cement ratio less than 0.45, achieved using water reducing agents / superplasticisers. Modern superplasticisers, referred to as «hyperplasticisers» can provide w/c ratios between 0.35 and 0.4, whilst maintaining a slump of 20 cm.
- Use of pozzolanic materials such as silica fume and PFA. Silica fume has a definite filler effect in that it distributes the hydration products in a more homogeneous fashion in the available space. This leads to a concrete with reduced permeability, increased sulphate resistance and improved freeze-thaw durability.
- Control of micro-cracking to 0.2 mm by fibre reinforcement instead of mesh, thereby allowing autogenous healing.
- Controlled, low dosages of alkali-free accelerators for reduced reduction in final strength compared to base mix, significantly reduced leachates, reduced rebound and dust, and most importantly, to provide safe working conditions.
- Hydration control admixtures to prevent premature hydration of the mix before it is applied to the substrate. Pre-hydration may cause significant deleterious effects to the hardened physical properties of the sprayed concrete, such as low strengths and densities, and increased permeability.
- Applicable curing methods (see chap. **4.3**).



Permeability classes taken from: Concrete Society Technical Report No.31, (1988)

Figure 30: Permeability test and results for sprayed concrete using MBT alkali-free and modified sodium silicate accelerators

A range of permeability tests for site testing are defined in the Concrete Society (UK) Technical Report No. 31: Permeability testing of site concrete (1988). Included are three concrete classes having high, average and low permeability based on typical results from the test techniques. The permeability tests and ranges for sprayed concrete are identified in Figure 30, and the test result ranges for samples using MBT technology are also illustrated, clearly demonstrating sprayed concrete as a durable lining material.

6.5 Sulphate resistance of sprayed concrete with alkali-free accelerators

In terms of sulphate resistance, a number of tests have been carried out by SINTEF, Norway and the results are summarised in Table 8, with «high» denoting excellent sulphate resistance.

Table 8: Sulphate resistance of sprayed concrete (SINTEF, 1999)

Cement Type	OPC	OPC	OPC	OPC	SR
Aggregates: **alkali-silica reactivity**	reactive	reactive	non reactive	non reactive	slightly reactive
Microsilica	0%	6%	0%	6%	0% and 6%
w/c ratio	0.45	0.47	0.52	0.48	0.45 to 0.48

Accelerator & Dosage

Modified sodium silicate 5%	moderate	high	none	high	high
Modified sodium silicate 10%	none	high	none	high	high
alkali-free 5%	high	high	none	high	high
alkali-free 10%	moderate	high	none	high	high

none (no sulphate resistance):	greater than 0.1% expansion
moderate sulphate resistance:	between 0.05% and 0.1% expansion
high sulphate resistance:	less than 0.05% expansion

A number of comments can be made regarding these results:
- Alkali-free accelerators can be used to produce sulphate resisting sprayed concrete up to dosages of 10%.
- Alkali-free accelerators perform better than modified sodium silicate accelerators with OPC cements.
- The use of 6% microsilica provides comparable sulphate resistance with OPC as sulphate resisting cement (SR). This is important as it is preferential to use OPC rather than SR cement in sprayed concrete due to the faster setting and early strength development.

- The lower the water-cement ratio, the higher the sulphate resisting performance. It is recommended to have a w/c ratio below 0.45 and preferably, with the aid of new hyperplasticisers, to attain a w/c ratio of less than 0.4.

6.6 Chemical stability of new accelerators

Recent microanalyses have shown that the sprayed concrete samples comprising accelerating admixtures contained similar mineral phases to those present in a control concrete. Additionally, both the control and admixture samples showed similar microcracking patterns. The studies concluded that the lack of differences, both chemically and structurally, posed no adverse implications for long term durability of sprayed concrete containing accelerating admixtures. Furthermore, petrographic studies of permanent sprayed concrete demonstrate that early-age thermal microcracking is a temporary feature removed by the onset of autogenous healing. No evidence has been found through permeability, compressive and flexural strength tests, that early age microcracking causes any detrimental effects to the stability or durability of the concrete.

6.7 Durability of steel fibre reinforcement

The main durability benefit of steel fibre over weldmesh reinforced concrete, in severe environments, is that it will not support the common galvanic corrosion cells which often lead to considerable damage to conventionally reinforced tunnel linings. The risk of concrete spalling due to corrosion is eliminated as the increase in volume due to the corroded fibre is insufficient. Additionally, the fibres, which are discrete, are protected by an alkali matrix. There is, therefore, no mechanism for the propagation of corrosion activity, as reviewed by numerous case histories and research studies of structures exposed to highly saline and freeze-thaw environments. It is therefore unnecessary to opt for stainless steel fibres to achieve durability.

Plain steel fibres exposed at the concrete surface will tend to leave rust spots. Therefore, for cosmetic and safety reasons, it is recommended that permanent steel fibre reinforced sprayed concrete linings are protected by a thin finishing mortar layer containing the new HPP 152 polymer fibres for thermal cracking control.

6.8 Application requirements

Quite often, the benefits of a well engineered mix design to achieve the durability requirements of the structure are negated by poor application processes (see chap. **10** for more details).

6.9 Conclusion

- To achieve durable sprayed concrete linings, the development of the concrete mix design is only but one facet that needs to be accomplished. The production of durable sprayed concrete is significantly reliant on human skills during spraying and equipment that is fit for the purpose.

- The designer also has a key role to play. The important issues in this case are to understand the sprayed concrete application process and not to over specify material properties. The key to achieving durability is through «buildable» designs by keeping details as simple as possible.

- Wet-mix sprayed concrete applied using modern, high performance, environmentally safe admixtures and equipment provides the tunnel industry with an economical tool to construct permanent, durable single shell linings. The construction process has become highly automated thereby significantly reducing the degree of human influence that has, in the past, prevented clients from considering sprayed concrete as a permanent support.

- Modern sprayed concrete specifications now address the issues of achieving a quality controlled modern mix design, providing guidance on promoting durability and effective execution of the spraying processes. As an example, the new European Specification for Sprayed Concrete (1996) by EFNARC, provides comprehensive systems to attain permanent sprayed concrete.

- With the increased use of durable sprayed concrete linings, new technologies to promote and maintain their use have entered the market recently. These systems enhance watertightness and provide high performance fire resistance.

- Further implementation of durable sprayed concrete for tunnels and other civil engineering structures is increasing, with a marked change during the mid 1990's. This trend is set to increase further as design and construction teams become more familiar with modern sprayed concrete technology and the durable concrete that can be produced.

6.10 Example of C-45

Cement	450 kg
Microsilica	20 kg
Fine gravel	0–8 mm
Glenium® T803	2.5-3 kg
Polymer fibres	7.5-10 kg
w/c+s	0.40
Spread table	>55 cm

Addition at the nozzle:	
MEYCO® SA160/SA161	4-8%

This mix is stabilized for more than 3-4 hours (thanks to Glenium® T803).

The final strength of the concrete must be higher than the specified strength. Provided materials, mix design and execution of spraying are correct, a rough estimate should aim at obtaining one strength class higher for the final strength than the specified requirement.

6.11 Consequences of using different mix designs

To obtain soft consistencies (>25 cm) is very critical. The high dosage of accelerator needed gives a big decrease in final strength, and there is a risk of segregation and clogging.

Low cement dosages (<400 kg) give a very small margin with regard to sub-standards and require a firm control of the accelerator dosing and hardening conditions; lower production capacity and dramatically increased rebound.

Overdosing of microsilica (12–15 %) gives a very sticky concrete which is very difficult to pump. This must be compensated for with a higher slump.

A high content of coarse aggregates (for instance 20 % larger than 4 mm), gives a higher rebound loss.

Crushed aggregates cause heavy wear on pumps and hoses and large losses through rebound. There is also a risk of dehydration and clogging.

Large amounts of fibres (long fibres) create pumping and compaction problems: cavities around fibres, poor mechanical properties, poor resistances and inferior adherence to the surface. A reduction of the fibre length helps.

7. Sprayed concrete equipment

Typical for the underground environment are numerous technical solutions, high risks and time pressure. Consequently, the contractor needs a competent and reliable partner. However, quality products alone are not enough. Only with a balanced utilisation of reliable equipment, high performance products and competent service can the required quality and efficiency be achieved.

Parallel to the development in material technology there has been a constant innovative development in the equipment sector to produce machines suited for the new products and that are adaptable to the everchanging conditions in the construction business. The result is a wide range of systems that cover all sprayed concrete works: from huge tunnelling jobs with large quantities of concrete mixes to be sprayed down to small volume repair works. Common to all developments in equipment is the tendency toward integrated and automated systems which ensure higher production output, consistent and controllable quality, as well as safer and more operator-friendly working conditions.

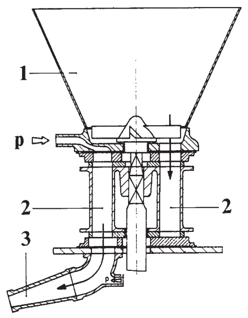
7.1 Manual application

7.1.1 Equipment/systems for dry-mix spraying

Machines that work on the rotor principle are the type most generally used nowadays.

7.1.1.1 Operating principle (e.g. MEYCO® Piccola, MEYCO® GM)

The dry mix is filled into the feed hopper (1); see Fig. 31. As the rotor revolves the mix alternately falls, by its own weight, through a feed slot into one of the rotor chambers (2) placed below. While one of the chambers is being filled, compressed air (p) is blown from above into the other (full) chamber. The mix is discharged into the outlet opening (3) and blown at a pressure of 3–6 bar through the conveying pipeline to the spraying nozzle where the mixing water is added. Top and bottom of the rotor are sealed with rubber discs.



1 = Feeding hopper
2 = Rotor
3 = Outlet
p = Pressurized air

Figure 31: Operating principle of rotor machine for dry spraying

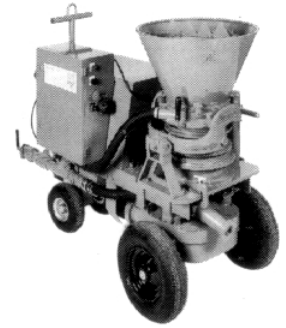


Figure 32: MEYCO® Piccola / MEYCO® GM: Typical rotor dry-mix spraying machines

The essential advantages of this machine are simple operation, sturdiness and adaptability to the specific conditions of the site. Depending on the diameter of the outlet and the conveying tube as well as the type of rotor, practical outputs range from ~0.5 m³/h to ~10 m³/h.

If the spraying output is raised by increasing the chamber volume and the revolving speed, the conveying tube has to be redimensioned accordingly. For spraying, the maximum diameter is 65 mm, whereas for conveyance only, e.g. for placement behind formwork etc., diameters of up to 80 mm can be used. With growing tube diameters, the compressed air consumption will also increase.

There are more parameters determining the size of the conveying tube: the granulometry of the dry-mix, the grain shape of the aggregates, compressed air supply, the conveying distance and height.

Figure 33: Various nozzles for dry-mix spraying

7.1.1.2 Developments

Developments in dry-mix spraying equipment are going towards improved dust-proofing, low filling height of the rotor chambers to ensure an even flow of the mix, and improved wear resistance.

7.1.1.3 Integrated systems for manual application

For repair and reconstruction works compact and mobile systems containing all the tools necessary for spraying and independent of external power supply are required for maximum flexibility.

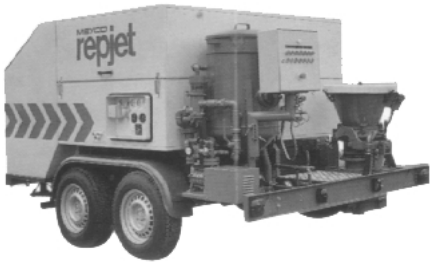


Figure 34: MEYCO® Repjet

The MEYCO® Repjet is such an example. The chassis is designed to take the following modules which can be built-in or mounted, as the case may be, and are all available as options:

- Integrated hydraulic pump unit (to drive MEYCO® Piccola and accessories)
- High pressure water cleaner
- Dosing unit (for accelerators/activators)
- Stripping equipment

- Site illumination
- Remote controls
- Water pressure increasing pump
- MEYCO® Piccola dry-mix spraying machine
- Air compressor
- Sandblasting unit
- A.C. generator
- Diesel motor as power source

7.1.2 Equipment/systems for wet-mix spraying

In wet-mix spraying the professional applicators trust in double-piston pumps.

7.1.2.1 Developments

To ensure even spraying, the latest equipment developments aim at realizing a pulsation-free conveyance of the wet-mix from the pump to the nozzle. This is put into practice with MEYCO® Suprema from MBT: The electronically controlled push-over system that is integrated into the output adjustment brings the pulsation of the material flow to a minimum which is hardly noticeable at the nozzle. An integrated memory programmable control system (PLC) supervises, coordinates and controls all functions of the machine. The PLC system allows checking and controlling of data which can also be printed out, e.g. dosing quantity of admixtures, output capacity etc. A dosing unit for liquid admixtures is integrated into the drive system of the machine and connected to the PLC system. This guarantees forcible regulation of the dosing analogous to the spraying capacity.

Main and important features:

- Three independent oil pressure circuits, each of them fed by a separate pump.
- S-shaped quick selector valve with special high pressure control system (auxiliary pump with topped accumulator).
- To prevent blockages, the direction of the feed pistons is reversible. When the maximum conveying pressure is exceeded, the pistons reverse automatically.
- The hydraulic cylinders have an automatic stroke adjustment.
- Special push-over system through a proportional valve in coordination with the PLC control system. As the electronically controlled push-over system is linked with the material output adjust-

ment, the pulsation over the full range of the material flow is reduced to a minimum and hardly noticeable at the nozzle.

- The PLC system supervises, coordinates and controls all functions of the machine. It also allows checking and controlling of data which can also be printed out, e.g. dosing quantity of admixtures, output capacity etc. Errors within the hydraulic or electrical systems will be indicated on the display, the causes of malfunctions can be determined through the help program of the PLC and will be indicated on the display.
- MEYCO® Dosa TDC dosing system for liquid admixtures. This integrated proportioning unit is an infinitely variable mono pump (screw pump), with flanged-on electric motor (frequency controlled) which is connected to the drive of the feed (concrete/hydraulic) pistons through the PLC system. This guarantees a forcible regulation of the dosing capacity analogous to the spraying capacity.

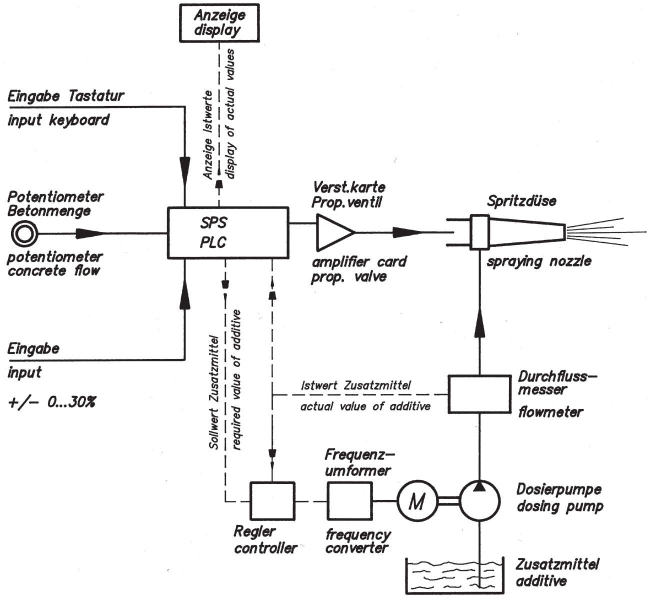


Figure 35: Working principle of the MEYCO® Dosa TDC (Total Dosing Control) system

Technical data of MEYCO® Suprema

Max. conveying capacity, theoretical	2-14 m³/h or 3-20 m³/h
Conveying distance, horizontal	300 m
Conveying distance, vertical	100 m
Air consumption at nozzle	
hand spraying:	5–7 m³/min. at 5–6 bar
robot spraying:	10–15 m³/min. at 7 bar
Dimensions	L = 2’500 mm, W = 1’520 mm, H = 1’950 mm
Feeding height	approx. 1’100 mm
Weight, empty	approx. 2’200 kg
Max. concrete pressure	75 bar or 50 bar
S-tube switch	150/125 mm
Conveying tube	50 mm, 65 mm or 100 mm
Integrated dosing unit	mono (screw) pump

Figure 36: MEYCO® Suprema: pulsation-free spraying, computerized control system (PLC), integrated dosing system to allow automated regulation of the dosing to the spraying capacity

7.1.2.2 Integrated systems for manual application

For various tunnelling jobs, such as grouting, backfilling, repairing and reprofiling, the processing of ready-to-use sprayable mortars is needed. Versatility, flexibility, compactness and ease of handling are the main requirements. An example is the MEYCO® Deguna 20T, a mono pump (worm pump) with integrated mixer. Its output is adjustable from 5–40 l/min. (mechanical variator); the maximum mortar pressure is 40 bar.

Figure 37: MEYCO® Deguna 20T

Another proven example is the Rambo sprayed concrete pump (15 kW). It has been specifically developed as a cost effective unit for spraying in areas where compactness and ease of handling are critical. The unit has an output of approximately 5 m^3/hour and contains a mono pump for accelerator dosing. The total weight of the skid mounted version is 950 kg whilst railcar and rubber wheel mountings are also available.

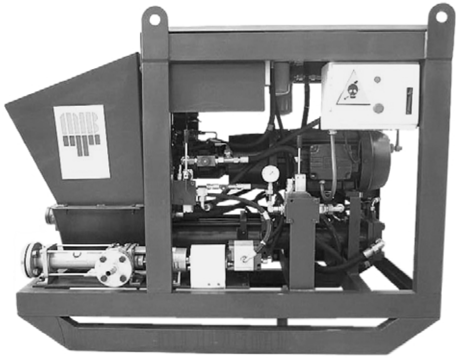


Figure 38: Rambo double piston pump

7.2 Mechanized spraying

7.2.1 Spraying manipulators

Spraying manipulators or robots are suitable for use wherever large quantities of sprayed concrete are applied, especially in tunnel and gallery constructions or for protection of building pits and slopes. Thanks to mechanized and automated equipment even large volumes of sprayed concrete – dry-mix and wet-mix – can be applied under constantly optimum conditions and without fatigue for the nozzleman who also profits from higher safety and improved general working conditions.

The spraying robots typically consist of:
- Lance-mounting with nozzle
- Boom
- Remote control
- Drive unit
- Turntable or adapter-console (for different mounting versions)

Figure 39: MEYCO® Robojet spraying manipulator

The lance-mounting allows any movement of the jet that is possible or necessary for spraying. Lance-mountings are available in lengths of 1, 2 or 3 metres. The lance-mounting is attached to the boom, which can be moved in any direction and lengthened by means of a built-in extension. It is controlled by a portable remote-control.

The MEYCO® Robojet, for example, has 16 separate individual movement functions that are controlled by means of 4 operating levers. Routine operations, such as horizontal back and forth movements or circular movements of the nozzle, can be automated. The spray-head is powered by three separate independent hydraulic drives, thus ensuring that the nozzle is always operated at the ideal angle to the surface. The nozzle can be turned 360°, clockwise or counter-clockwise. The lance mounting is automatically held parallel to the axis of the tunnel. The remote control is equipped with a 20 meter long cable and can thus be operated from a safe location. The drive unit can be set up in various ways depending on the mounting. Power is supplied from an own electrically driven power pack. It is also possible to have it powered by the carrier. The MEYCO® Robojet can be mounted onto various kinds of carrier vehicles, e.g. on an excavator chassis, on a truck, on a TBM etc.

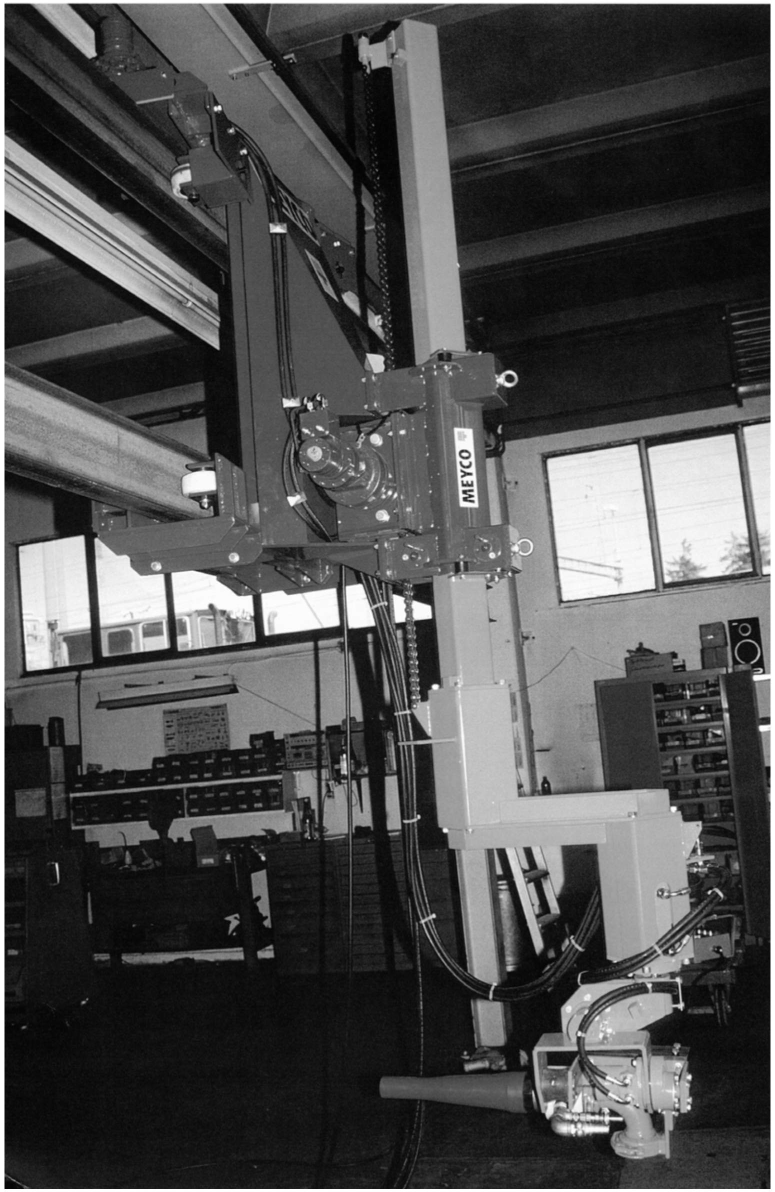


Figure 40: MEYCO® Robojet shaft manipulator

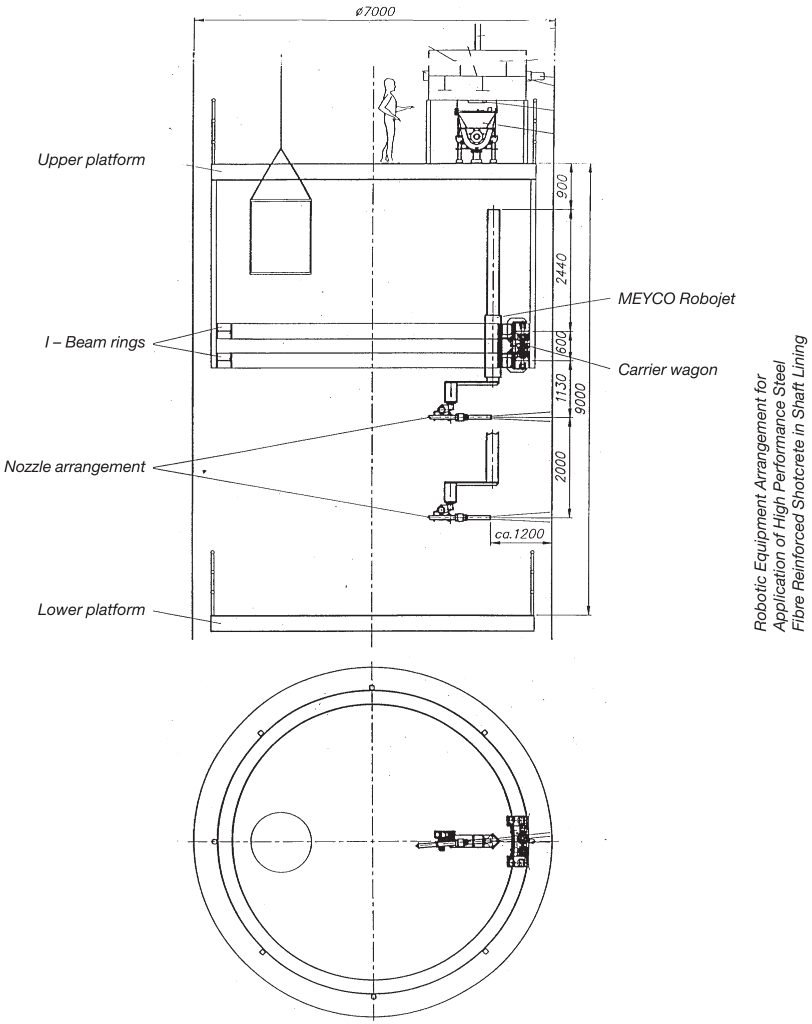


Figure 41: Example of shaft sinking platforms

Figure 42: Tailor-made solution by MBT: The MEYCO® Robojet spraying manipulator is integrated into a small diameter TBM.

Figures 40 - 43 show integrated concepts for TBM's and mechanized excavation systems. Design and build are based on modular concepts to meet most sprayed concrete requirements and specifications in tunnelling and shaft sinking.

Figure 43: Tailor-made solution by MBT: The MEYCO® Robojet spraying manipulator is integrated into a large diameter TBM.

7.2.1.1 Computer controlled spraying manipulators

The MEYCO® Robojet Logica is a new state-of-the-art spraying manipulator which has been developed in cooperation with the industry and universities. It has eight degrees of freedom and enables the operator to manipulate the spraying jet in various modes, from purely manual to semi-automatic and fully automatic, within selected tunnel areas. In one of the modes, the operator uses a 6-D joystick (space mouse).

The aim of this computer controlled spraying manipulator is not to automate the whole job of spraying but to simplify the task and enable the operator to use the robot as an intelligent tool and to work in an efficient way with a high level of quality. Thanks to the correct spraying angle and constant spraying distance which are maintained at all times, a remarkable reduction in rebound and therefore cost savings are achieved.

The new machine is based on the world-wide well known kinematic principle of the MEYCO® Robojet. The calculation of the kinematics is done by a control system. A laser scanner sensor measures the tunnel geometry and this information is used for the automatic control of the distance and the angle of the spraying jet. Furthermore, if the tunnel profile is measured again after spraying, the system will provide information on the thickness of the applied sprayed concrete layer which was up to now only possible with core drilling and measurements. If an exact final shape of a tunnel profile is required, the

Figure 44: MEYCO® Robojet Logica

control system operates the robot to spray to these defined limits automatically.

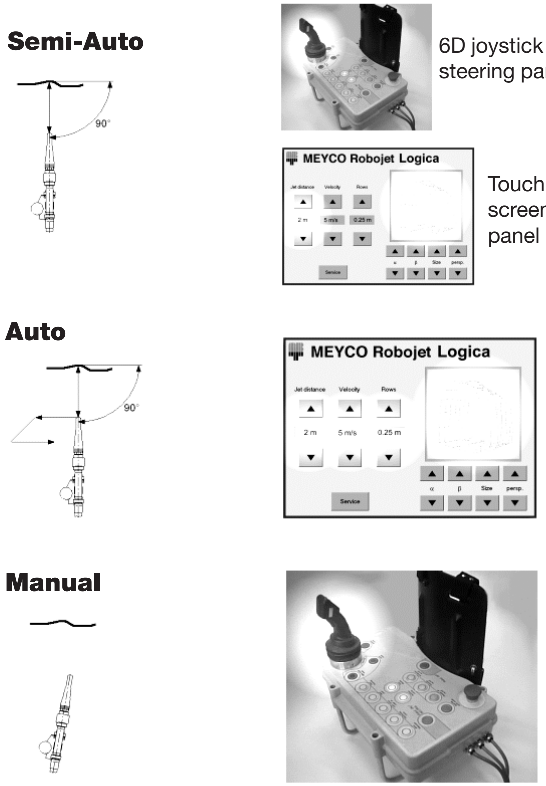


Figure 45: Working modes of MEYCO® Robojet Logica

7.2.2 Spraymobiles

The new MEYCO® Potenza Spraymobile has been developed by MBT based on the extensive experience gained over more than 15 years of building spraymobiles. It combines an operator friendly manipulation with a 30% higher output capacity (max.). All necessary equipment to perform spraying works under economical aspects are built in:

- MEYCO® wet-mix spraying machine
- MEYCO® Dosa TDC dosing system for liquid accelerators

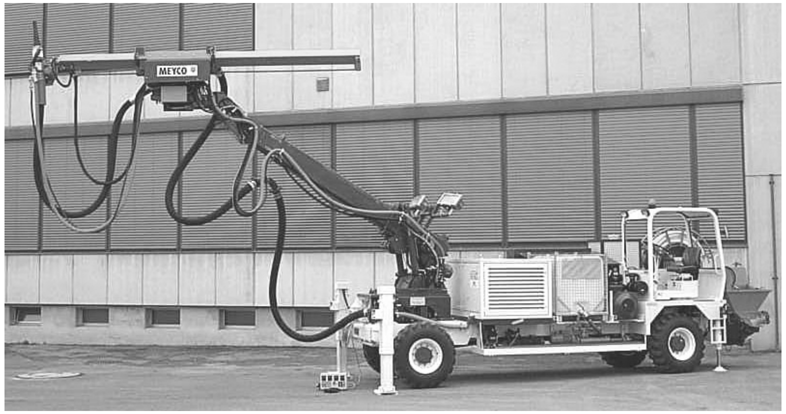


Figure 46: MEYCO® Potenza Spraymobile: The modular system allows building of spraying systems to customers/products demands and needs.

- MEYCO® Robojet or Robojet Compacta spraying manipulator
- Accelerator storage tank
- Air compressor
- Cable reel with hydraulic drive, incl. cable
- Electro-hydraulic power pack
- Central control system (only one)
- Remote control with cable or radio remote
- High pressure water cleaner, incl. water tank
- Working lights
- Central lubrication system
- 4-wheel drive, 4-wheel steer chassis with Diesel engine

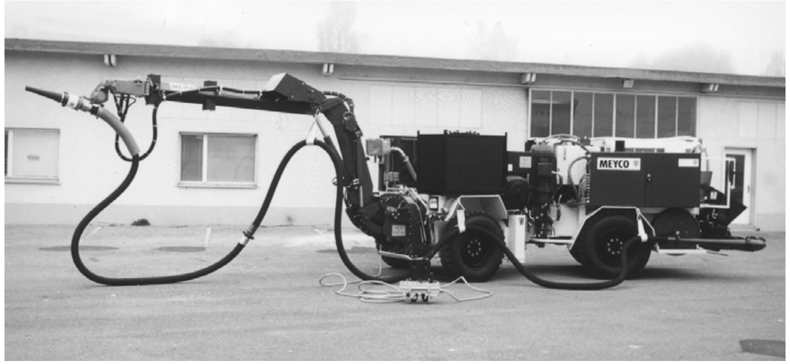


Figure 47: MEYCO® Cobra Spraymobile: Mining version.

Figure 48: MEYCO® Mamba Spraymobile: Mining version.

Figure 49: MEYCO® Roadrunner 2000: This mobile spraying system contains all specified equipment of the MEYCO® Spraymobile, mounted on a roadworthy truck. All equipment can be powered either from an external source or by its own Diesel motor. In addition to the MEYCO® Spraymobile it also contains a tank for curing agent.

7.2.3 Benefits of mechanized spraying

- Reduced spraying cycles due to higher output capacity and the elimination of time-consuming installation and removal of the scaffolding, particularly in tunnels with variable profiles.
- Cost savings thanks to reduced rebound and labour savings

- Improved quality of the in-place sprayed concrete thanks to even spraying
- Improved working conditions for the nozzleman thanks to protection from cave-ins, rebound, dust and accelerators.

7.3 Dosing systems

When using liquid admixtures it is important to ensure that dosing is constant and uniform in relation to the weight of the binder. To achieve this, the use of an appropriate dosing pump (e.g. MEYCO® Mixa) is necessary.

Figure 50: MEYCO® Mixa 15

7.4 Nozzle systems

Nozzle systems are an important part of the spraying equipment. Nozzles essentially contribute to providing:

- Lower rebound
- Improved bonding
- Improved compaction

through:

- Proper mixing of accelerators/activators and air in the case of the wet-mix spraying method
- Proper mixing of accelerators/activators and water in the case of the dry-mix spraying method

Only with the correct nozzle system (e.g. from MBT) – adapted to the type of application (wet-mix/dry-mix method, robot/hand application) and the accelerator/activator used – can low wear and outstanding quality of the in-place sprayed concrete be obtained.

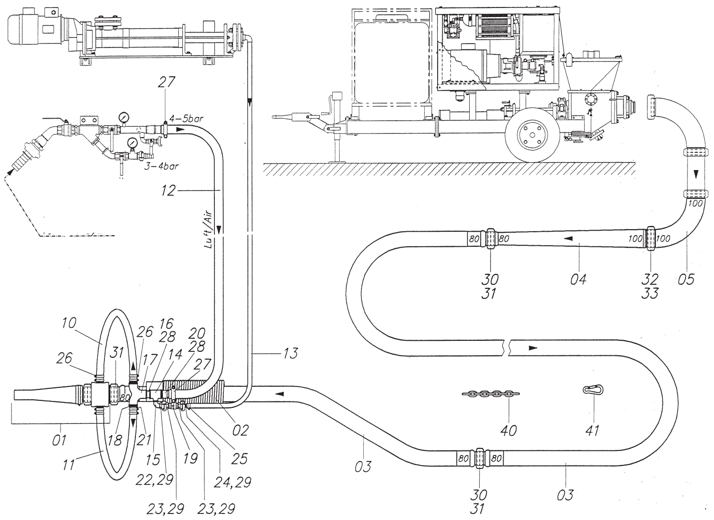


Figure 51: Nozzle system for modified silicate based and alkali-free accelerators, for robot application

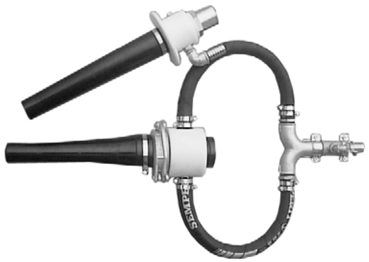


Figure 52: Typical nozzle for wet spraying; for use with manipulator and for manual application.

7.5 Systems for strength development measurements

7.5.1 Penetration needle

The penetration needle measures the early strength curve up to about 2 hours. It is an indirect test method, using a needle of defined dimensions which is pushed with a defined force to a defined depth into the fresh sprayed concrete. The resistance measured is an indication of the compressive strength of the sprayed concrete.

To be precise, this method actually measures a combination of compressive and shear strengths, or the resistance to local plastic deformations. The aggregates contained in the sprayed concrete and the support behaviour of the granulometry strongly affect the results.

Figure 53: MEYCO® Penetration Needle

7.5.2 Pull-out test

The pull-out test determines the strength development from 3 to 24 hours. This method measures the force that is needed to pull out a draw bolt imbedded in the sprayed concrete. From this force and the surface area of the torn-out, truncated cone specimen, it is possible to calculate the shear tensile strength and consequently the compressive strength of the green sprayed concrete at the time of testing.

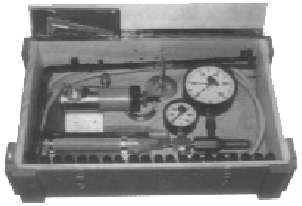


Figure 54: MEYCO® Kaindl early strength measuring instrument

8. Rock support design

One of the typical features of sprayed concrete as a support method, is the extremely good usage flexibility, as compared to formwork and poured concrete lining, or any other possible alternative. The only way of fully getting the benefits of this property, is to use sprayed concrete as part of the final lining of the tunnel, adapted to the varying rock conditions. The important subject of rock support design gives the basis for what can be achieved in this context. The subject is therefore being presented in this Chapter, to establish what we consider the right principles to apply.

Rock support design is a specialised field, and it is fundamentally different from the design of other civil structures. The design procedure for rock support therefore has to be adapted to this situation. The reasons are the following Facts of Life:

- The primary «building material» is rock; thus, the material properties are given and yet only partly known.
- The «building material» is highly variable, sometimes within short distance.
- There are severe limitations in what information can be provided by means of geological investigations.
- There are limitations in accuracy and relevance of rock material parameters than can be tested.
- There are severe limitations in calculation and modelling methods.
- The behaviour of openings is time dependent, and also influenced by changes in water conditions.
- There is an incompatibility between necessary time for parameter testing for calculations and modelling, compared to available time: Progress of excavation is far higher than the capacity in the mentioned activities.

It is therefore quite obvious that any successful design approach for underground openings must be, or should be, adapted to this situation. Some sort of «design as you go» system is the only reasonable basic method.

In real life, many tunnelling projects are still designed in a different way. The designers sometimes produce a support design based on pre-investigations of the rock mass and the traditional load/capacity/safety-factor approach. This unavoidably leads to a «worst case» design, which may be necessary in only a small part of the tunnel.

Analytical and numerical calculations

Calculation tools are an important part of rock support design. To be able to calculate loads, stresses, deformations, support capacity, etc., input parameters must be established and the formulas and numerical modelling programs must be available. To a varying degree, this will require:

- Sampling and testing for a number of different rock material parameters
- Testing of discontinuity (joint) parameters
- Measurement of in situ rock stresses, often in long boreholes
- Investigations of ground water conditions
- Analysis of geometrical data (tunnel shape, intersections etc)
- Analysis of scale effects on laboratory parameters
- Analysis of the openings to be excavated and the excavation sequences
- Identification of rock support material parameters

Analytical calculations can be quickly performed and are well suited for rough preliminary estimates. The possibilities are quite limited in more complex situations.

Numerical analysis (Finite Element Modelling) is normally run as 2-dimensional models in computers. Even relatively simple situations may take days of preparation and run-time, before results are available. Once some basic work for a given project has been carried out, sensitivity analysis and re-calculation based on new, or updated information, can be more quickly performed.

Numerical 3-dimensional modelling is normally so demanding that only mainframe computers can cope with such tasks.

Evaluation of empirical and calculation design methods

Empirical methods for the design of rock support can be used as a design tool by classifying the rock immediately upon exposure. The classification system's recommended rock support can then be installed. This approach takes care of the variation in rock quality as it is actually encountered and is not dependent upon presumptions concerning rock quality. The Q-method developed by the Norwegian Geotechnical Institute (Dr. Nick Barton et. al.) is probably the best established method of this kind.

Calculation methods on the other hand are generally too slow to cope with tunnelling progress and the often quick variation in rock quality. Sampling, testing and calculations for a given situation in the tunnel, would take days. Obviously, the tunnel support works and face advance cannot wait for a completion of these steps.

In the case of a more specific location like a cavern for a powerhouse, railway station, etc., calculations can be very useful and can more easily fit into the job site progress.

The basic limitation still remains that all input data, formulas and numerical models contain a lot of uncertainties and approximations. The accuracy of results is therefore sometimes very poor and it is hard to tell when and where that will be the case.

A special feature of blasted rock surfaces is the extremely complicated geometry. A relatively thin (50 to 200 mm) layer of sprayed concrete cannot smoothen this contour into a defined arch geometry. The complicated interaction of ground response over time, compared to the sprayed concrete hydration and strength gain over time, variation in sprayed concrete thickness and variation in bond strength, also increase the complexity of calculations.

The Observational Method

The Observational Method has in reality existed since man started tunnelling. In the beginning, and also today, this approach is being used out of common sense and sometimes bare necessity and it reflects the consequences of the above described Facts of Life.

The basic elements of the method are as outlined below:
- Rock support shall be designed for expected rock condition variations as a *rock support prognosis.* In this design work, any and all kinds of empirical and calculation methods can be used, as considered necessary and useful.
- *Verification of the prognosis* shall take place after excavation and support installation, by visual inspection, monitoring of deformations, stresses, loads, water pressure and any other means as considered necessary. Adjusted or added support may become necessary, locally, also subject to verification.
- The prognosis shall be *updated by feedback* of data from previous steps, to decide upon possible design adjustments.

The advantages of the Observational Method are obvious. The mountain is being used as a full scale «laboratory», where known and unknown parameters are involved and covered. It allows a flexible work procedure, immediate action when necessary and support adapted to the actually encountered conditions. Normally, this gives more balanced and less costly solutions.

In a major part of modern tunnelling activity, the Observational Method is today the accepted basic approach. As presented above, it is of course only a framework that needs a lot of detailed decision-making in a real tunnelling case. It is still important to understand why this approach is the only reasonable way of making design underground. The pre-designed solutions based on a normal structural design approach with codes and standards, as for steel and concrete structures like bridges and buildings, are simply not applicable.

The very well known New Austrian Tunnelling Method (NATM), is a procedure covered by the more general approach of the Observational Method.

8.1 Active mechanisms of sprayed concrete on rock

Even when applying the Observational Method for rock support, it is useful to understand why and how thin layers of sprayed concrete can have such an outstanding stabilising effect. Such understanding is also an important basis for evaluating combinations with other support measures and the limitations of the solutions.

There are some important characteristics of the sprayed concrete application process which one should keep in mind:
- Concrete is blown against the rock surface at a high velocity of 20 to 100 metres per second, depending on method and equipment.
- The rebound consists mainly of coarse particles. The amount of rebound is greatest at the first hit. At a later stage of spraying, when semi-soft concrete covers the surface, more will stick. The effect of this is an increase of fines directly on the rock surface.
- The applied concrete is compacted by the immediately following impacts (layers).

- The sprayed concrete layer will stick to the surface with a bond strength (adhesion) of up to 3 MPa.
- The rock surface is completely encapsulated.
- Fines are, to some extent, squeezed into cracks and joints.

The stabilising effects which can be identified from the above characteristics, are:

- Mortar and fines squeezed into the cracks and joints in the rock contour produce a wedging effect like mortar between bricks in a wall or arch.
- Punching resistance, which means that a loose block can only fall by shearing through the sprayed concrete layer.
- Arching effect; sometimes only local arches are actually working.
- Insulation against changes of moisture, effects of air and temperature, washing effect from running water etc.
- Maintenance of the existing stability at the time of application.
- Simultaneous and combined effect of the above mentioned mechanisms.

For thin sprayed concrete layers, it is obvious that the mode of operation is much more like a rock reinforcement than a rock support. On the rock surface there will be a composite action between the rock substrate and the hardening concrete. Practical experience shows that even a 30 mm sprayed concrete layer is very effective in some situations. This observation supports the basic idea of a composite action.

8.2 Sprayed concrete on jointed hard rock

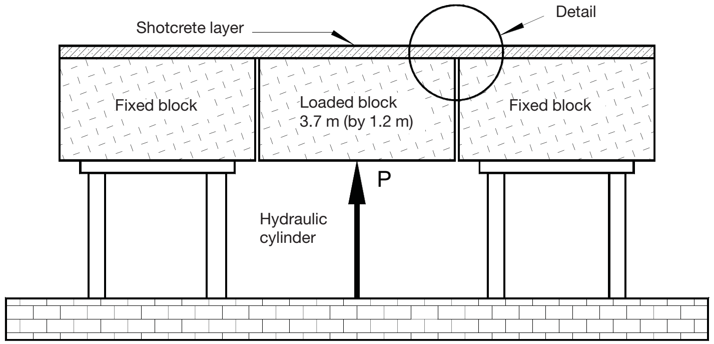


Figure 55

During the seventies and beginning of the eighties, a number of large scale model tests were carried out in Scandinavia and North America. It is beyond the scope of this Publication to present all these results. However, some simple tests and their results may be very illustrating.

Dr. Jonas Holmgren in Sweden used a test rig as shown in Fig. 55. The sprayed concrete layer was flat (no arch effect) and concrete material was prevented from entering the opening between the blocks (no brick mortar effect). By varying the layer thickness of sprayed concrete and measuring loads and deformations, Holmgren was able to pinpoint some important facts.

Up to a layer thickness of about 30 mm, the moving block would simply punch through (shearing through) the sprayed concrete. This result is not surprising and the load taken is directly linked to the shear strength of the sprayed concrete and its thickness.

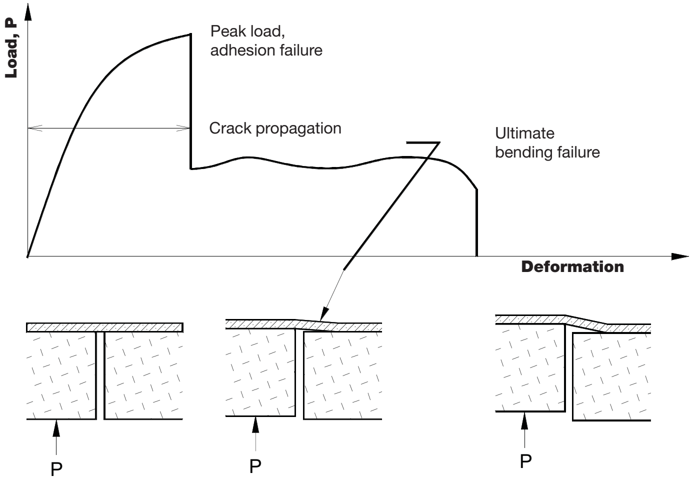


Figure 56

For layer thicknesses above about 30 mm (basically irrespective of the thickness), the tests showed that the bond strength was decisive. The basic behaviour of the model is illustrated in Fig. 56 (refer to the «detail» on Fig. 55). For normal, sound granitic rock, back-analysis of the test results indicated that the width of the loaded bond zone at peak load, was about 30 mm. For a quite normal bond strength of 1.0 MPa, this can be used for an illustrative calculation:

Volume weight of rock can be, $\gamma = 27000\ \mathrm{N/m^3}$

A cubical block of rock is chosen, with edge length, λ meters

Bond strength as mentioned above, $\tau = 1.0\ \mathrm{MPa} = 10^6\ \mathrm{N/m^2}$

Bond zone width at peak load, $\beta = 0.03$ m (as found by Holmgren)

Driving force is the weight of the block, $W = \gamma\lambda^3$ (see Fig. 57)

Resisting force is created by the bond zone along the four edges of the block, $F = 4\lambda\beta\tau$

At peak load, the driving force equals the resisting force and we may calculate the maximum theoretical block size, that can be held by the bond strength alone:

$\lambda = \sqrt{4\beta\tau/\gamma} = \sqrt{4 * 0.03 * 10^6/27000} =$ **2.11 m**

Expressed in terms of volume and weight, a block of more than 9 m^3, weighing 25 tons, could be kept in place. The effects of local arching, brick mortar effect and existing friction within the rock, has not been considered. Obviously, this calculation is just an example to illustrate an order of magnitude and should not be taken as a statement that 35 mm of sprayed concrete is sufficient to safely support such a block.

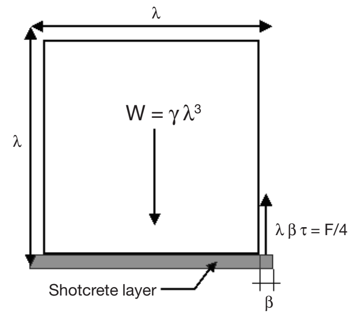


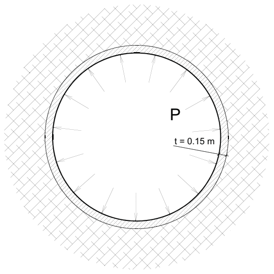
Figure 57

8.3 Sprayed concrete on soft or crushed rock

In many cases it is not possible or correct to envisage single blocks and wedges, locked in place by a thin layer of sprayed concrete. When tunnelling is carried out in generally crushed and weak materials, experience again still shows a remarkable short term effect of stabilisation, even with thin layers. In such situations the block and wedge theory and support mechanisms are not applicable. It is a bit more complicated to illustrate why and how it works under these conditions.

The most obvious reason for the immediate and short term effect is the maintenance of existing stability. Sprayed concrete produces a skin effect on the rock surface, preventing to a great extent differential movements in the contour. An inward deformation (convergence) will take place generally and evenly, not as local, differential stepwise deformations. As the contour moves inwards, the length of the contour tends to decrease, which means compressive forces in the rock/sprayed concrete composite. In this way the sprayed concrete is helping the rock material to carry itself. Again, we are looking at a reinforcement effect, rather than a load support. For this process to take place, the sprayed concrete shell needs to be of reasonable compressive strength with a good bond to the rock surface.

If the relation between rock stresses and rock strength does not allow a thin-layer, composite-action support solution, a structural sprayed or cast concrete ring may become necessary. The example of a TBM tunnel with a full, circular sprayed concrete lining is given in Fig. 58. In this case, the arch effect can be calculated and the bond strength is no longer a factor.



Shotcrete compr. strength	$\sigma_c = 35$ MPa
Thickness of shotcrete	$t_c = 0.15$ m
Tunnel radius	$R_i = 2.0$ m
Radially distributed load	P = ?

Maximum support pressure:

$$P = \frac{1}{2}\sigma_c \left[1 - \frac{(R_i - t_c)^2}{R_i^2}\right]$$

= 2.53 MPa = 253 t/m²

Figure 58

8.4 Basic rock mechanics

Excavating a tunnel will initiate changes in the stress field around the opening. If the stress is high enough and/or the rock is weak enough, the surrounding rock will move slowly into the free space (in addition to the small effect of elastic relaxation). This inward radial deformation (convergence) may be controlled and stopped by support measures, or it may continue until a broken zone of rock collapses into the tunnel.

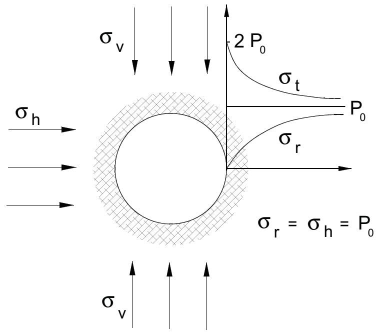


Figure 59

Fig. 59 shows a circular tunnel in a stress field where $\sigma_h = \sigma_v = P_0$. The radial stress σ_r and the tangential stress σ_t just before excavation are also shown. The rock material is considered as elastic.

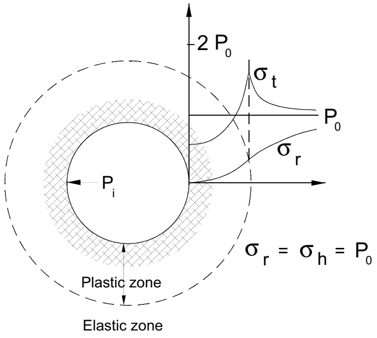


Figure 60

A short time after excavation, the stress situation will have changed and if the rock is weak enough, a crushed zone will develop as shown in Fig. 60. The radial deformation resulting from such crushing (plastic deformation) is also termed squeezing. In this simplified case the plastic zone is circular and concentric to the tunnel. If some support is established, the P_i of the figure represents the support pressure against the rock surface.

The magnitude of deformation and the thickness of the plastic zone depend on the inner friction and other strength parameters of the rock material. The stress magnitude is also an important factor.

When designing the rock support necessary to limit and stop deformation, the ground reaction curve and the support response curves are useful. This is a different way of illustrating what is happening, from what is shown in Figures 59 and 60. A ground reaction curve is shown in Fig. 61. This is an idealised load/deformation curve, describing the radial deformation depending on the support pressure. The ground reaction curve expresses in a given point the necessary support pressure to balance the load and stop further deformation. Line no 3 in Fig. 61 shows a case where the rock is overloaded and a plastic zone is created.

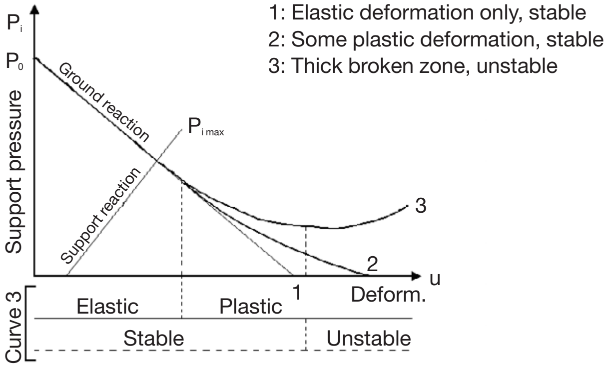


Figure 61

In the elastic part the load decreases when deformation is allowed to take place. At a low stress situation, the straight elastic line could continue to zero load, as shown by the broken line no 1. In this case, no support would be necessary.

At a slightly higher stress level a thin plastic zone would develop, indicated by the broken line no 2. If the stress level is high, we may follow the solid line no 3. The reason for the load increase is the weight of the broken material in the plastic zone of the roof. This gravity effect does not apply to walls and floor.

Installed support measures will be loaded by the rock deformation along a given response curve. Figure 61 illustrates that the support has been installed after some initial deformation has already occurred. The maximum load and deformation capacity of the support is also shown. The intersection point between ground and support reaction curves defines the final support load and the total rock deformation.

The diagram demonstrates the combined effect and interaction between the rock itself and installed support measures. It is important that support measures be installed at the right time, with sufficient load capacity and with the correct stiffness.

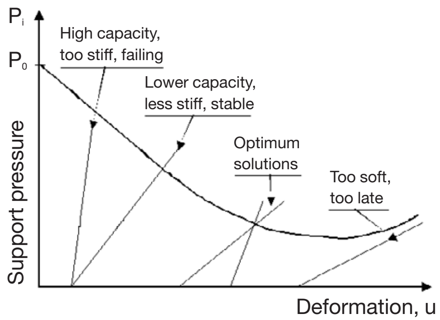


Figure 62

Figure 62 shows some support characteristics which illustrate the principles. A strong and stiff support may be overloaded, while a weaker and more ductile support is satisfactory. It is also possible that the stiff support works well, if installed at a later stage. The focus should be on optimising the support, which means letting the rock material carry as much potential load as possible.

8.5 Some points on NATM

NATM can be classified as an Observational Method. This becomes evident through the practical steps normally performed when using NATM.

- Collection of geological data, rock mechanics data and processing of this material in combination with tunnel dimensions etc. Processing means producing a load and deformation prognosis for a set of rock quality cases, covering the tunnel alignment. Any calculation tool which is regarded as helpful may be used in the prognosis development.
- A preliminary support plan is produced based on the previous step. Thickness of sprayed concrete, number, length and strength of rock bolts, type and spacing of ribs etc., is part of this plan. Prognosis of deformation speed and magnitude for different situations is important information in order to decide on the excavation/support sequence and the interpretation of monitoring data.
- The tunnel excavation proceeds according to the preliminary plan with necessary adjustments for observed rock quality.
- Monitoring instrument sections are installed at intervals in the excavated tunnel. These may include extensometers, convergence measurement bolts, load cells in the lining, load cells on rock bolts etc. The behaviour of the support members and the combined system of rock and support shall be constantly monitored.
- The final support is decided after monitoring the tunnel for a sufficient time. Depending on the design requirements and philosophy, this might give no additional support or in some cases a full concrete lining.

The NATM philosophy aims at allowing a controlled deformation to take place, so that the support system carries a load as small as possible. In practical terms this will normally lead to using sprayed concrete as a first support measure. Normal thickness may vary between 50 and 300 mm. It is normal that also sprayed concrete reinforcement (wire mesh or steel fibres) and rock bolts are used. In weak rock and/or in tunnels of more than 50 m^2 light steel ribs or lattice girders are frequently mounted.

One very important detail in the NATM application is the closed ring support. As can be easily understood, a closed ring of anchored sprayed concrete support is a lot stiffer than a horse shoe shape. The total load capacity is also higher. The same applies to all kinds of rib support. Again the timing of such a ring closure against deformation speed and magnitude, is very important.

The discussion of mechanisms and principles of sprayed concrete for rock support (Sections **8.1** to **8.5**) is only meant as a limited illustration from a very wide and complex subject. Regardless of which name tag (Q-method, NATM, RMR etc) the designer will use for a chosen set of principles and procedures, we can only recommend using the general principles of the Observational Method.

In urban areas, tunnelling often means very shallow excavation depths with severe consequences in cases of failure. It may therefore be necessary and reasonable to shift the design focus in the direction of pre-decided support solutions, with less or no emphasis on load transfer to the ground itself. In many cities the ground conditions are well known in advance and will, more often than not, be some type of soil rather than rock.

8.6 Important properties of sprayed concrete for rock support

The relative importance of different material parameters for sprayed concrete depends on the type of stability problem. Thin layers applied to hard rock to prevent loose stones and wedges from falling out, depend mostly on adhesion. The compressive strength in such a case is of minor importance. The compressive strength, on the other hand, is the main factor when a thick closed ring support of soft ground is considered. In this situation the adhesion is of no interest at all.

Compressive strength can be used as an indirect indication of durability factors. The concrete shall be of satisfactory long term durability in the environment where it is applied. There may be a difference between a road tunnel with heavy traffic and a water transport tunnel in this respect. In most cases the sprayed concrete must meet a 35 MPa strength class according to a normal national standard test procedure. In Norwegian sub sea road tunnels this requirement is now a grade 45 MPa concrete.

Adhesion to the rock surface is generally an important parameter. The problem is that it is complicated to measure accurately and it varies a lot within short distances. Very often people are reluctant to specify the required adhesion in a contract, because the control results may cause more problems than is worth while. In our opinion the control focus should be kept on compressive strength, application

technique and cleaning of the surface in advance. In this way, the best possible adhesion that the surface allows, can be achieved.

The tensile strength of sprayed concrete is not so important. In design considerations this strength cannot be included anyway, because there is always a chance of shrinkage cracks in critical sections. Across a crack there is naturally no tensile strength. The same applies to the flexural strength of the sprayed concrete material itself.

It is important that the required compressive strength is achieved by a mix design that gives a minimum shrinkage. There are two reasons for this:
- Low shrinkage improves adhesion.
- Low shrinkage reduces cracking and improves durability.

To produce a low shrinkage, the content of fines and cement should be low, the w/c ratio should be low (generally less than 0.45) and application technique must be correct (good compaction and spraying at right angles). A curing compound after application, water spraying, or the use of a concrete improver (such as MEYCO® TCC735) should be a routine part of the work.

The thickness of the sprayed concrete layer is a design question. The contractor shall distribute the necessary concrete volume to meet the requirement as closely as possible. This is a practical problem, especially if the specified thickness is large (200 mm and more) and the full thickness is placed on a limited area during one operation. Under such circumstances the tendency is that the walls get more concrete than required and, of course, the roof gets less. This is the opposite of what is wanted, from a stability point of view.

This leads to a very important parameter in sprayed concrete application, the short-time strength development. Safety and economy are improved if the strength gain within the first minutes and hours is high. High early strength is possible when using accelerators. Economy is improved to a maximum if it is possible to build full thickness in one continuous operation, even on a limited area.

8.7 Reinforcement

The traditional reinforcement in sprayed concrete is steel wire mesh (normally 3 to 6 kg/m^2 and square openings of 100 to 150 mm). It is also named welded wire fabric (WWF). This product should never be replaced by the kind of nets used for fences (chain link mesh). Chain link mesh usually has a wire thickness of 2 to 3 mm and openings of 50 mm. Chain link mesh must not be used in sprayed concrete, due to the small openings and fluffy behaviour, which causes high rebound, a build-up on the net, and leaves voids behind it.

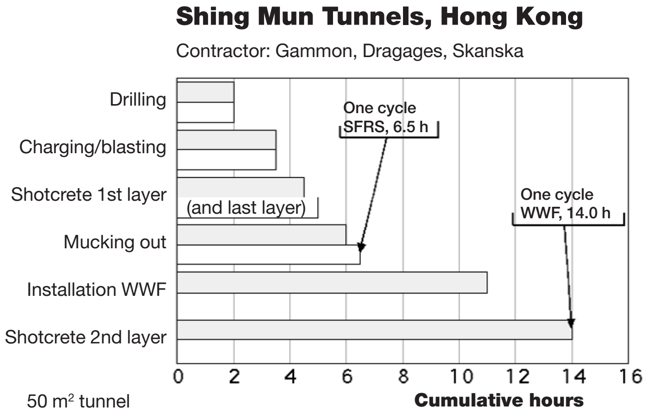


Figure 63

Installing WWF is highly manual work, and it is very hard to improve on its efficiency. The cost of reinforcement by WWF is hence constantly increasing, because the production capacity is fixed. The direct erection cost for WWF per m^2 is in the range of CHF 20 to 30. The substantial overall tunnelling capacity increase by switching from WWF to steel fibre reinforced sprayed concrete (SFRS) is shown in Fig. 63.

It is important to be aware of the purpose of reinforcement in sprayed concrete. In rock support there is the constant possibility of unexpected loads and deformations. The best possible safety margin is achieved by the highest possible fracture energy in the sprayed concrete layer. The fracture energy (toughness) is represented by the area below the load deformation curve, when testing beams under flexural loading, see Figure 64. Today, modern test procedures, such as the EFNARC test, are based on sprayed panels testing.

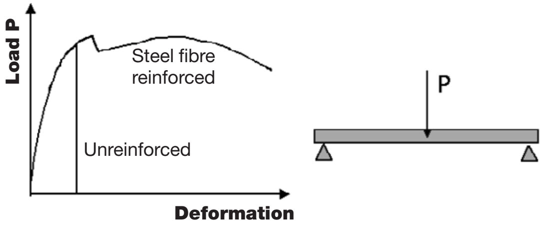


Figure 64

8.8 Tunnel support methods

Sprayed concrete has traditionally been considered a temporary support in most countries. Due to increasing pressure on economy, the interest for one pass tunnel linings based on sprayed concrete, has increased substantially during the last few years. High performance wet-mix sprayed concrete, where necessary combined with steel fibres, has become the first choice for this approach.

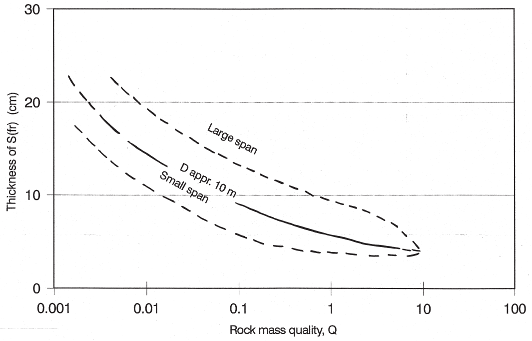


Figure 65

The most commonly used support combinations are: Rock bolts (sometimes with steel straps), sprayed concrete (usually steel fibre reinforced) and cast concrete using steel shuttering.

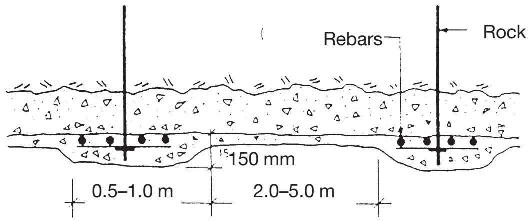


Figure 66: Support with ribs of fibre reinforced sprayed concrete

	Spacing between rock bolts			
	Q=0.1	*Q=1.0*	*Q=10*	*Q=30*
Areas without sprayed concrete	*1.2 m*	*1.4 m*	*2.0 m*	*3.4 m*
Areas with sprayed concrete	*1.3 m*	*1.6 m*	*3.0 m*	*4-5 m*

In recent years it has become more and more common in very poor rock conditions to replace the traditional cast concrete by steel fibre reinforced sprayed concrete combined with rock bolts and steel bar reinforced ribs of sprayed concrete, see Figure 66. This is a more adaptable solution than the pre-made lattice girders.

9. Permanent sprayed concrete tunnel linings

9.1 Development of permanent sprayed concrete tunnel linings

Conventionally, tunnels constructed using sprayed concrete have been based on a temporary sprayed concrete lining to stabilise the opening after excavation and to contain short to medium-term loads. When this lining has fully stabilised, a permanent cast in-situ concrete lining has been installed to contain long-term loads, and provide durability and watertightness, either by the use of a waterproof membrane between the temporary and permanent linings, or by the use of steel reinforcement to reduce crack widths to 0.2 mm to allow autogenous healing. This shall be referred to as the double shell method. Since 1994, sprayed concrete technology has improved dramatically in terms of stable admixtures and application methods, particularly with the wet-mix process to give a durable, high performance concrete.

In 1996, both the Jubilee Line Extension and Heathrow Express Rail Link projects constructed tunnel linings using permanent steel fibre reinforced sprayed concrete instead of conventional in-situ concrete within the temporary sprayed concrete linings, lowering costs and significantly reducing the construction time, particularly in sections of complex geometry.

The current state-of-the-art sprayed concrete technology equips the tunnelling industry with a considerably more economic tunnel lining system in the form of a single pass of permanent sprayed concrete, providing a structural lining that is also durable, watertight and can be surface finished to a degree that is similar, if not equal, to cast concrete.

The essence of the Single Pass Tunnel Lining method (SPTL) as described in this chapter, will be to maintain the design philosophy of the temporary sprayed concrete lining, but to enhance the material performance and construction control. This will permit the primary SPTL sprayed concrete lining to be considered as a permanent, durable structural element that will fulfil the structural requirements both during construction and throughout the designed life of the structure. This can be performed either as a true single shell, or, if required, acting monolithically with an additional sprayed concrete layer installed later during the construction process.

9.2 Cost effectiveness of single pass tunnel linings

SPTL can offer significant savings over the conventional double shell approach, by considering no part of the lining as a «temporary support», and by the reduction in excavation volume and required lining material, which leads to a reduction in construction time.

The SPTL one layer method can achieve a cost saving of 20 to 40% over a double shell structure, depending on tunnel cross section and length as well as rock conditions. When considering the cost of a tunnel constructed using the SPTL two layer method, there is a considerable difference between opting for a sprayed or cast in-situ second layer due to the high project start-up cost of a steel shutter for a cast in-situ second layer, as opposed to the non-shuttered option of a second layer of permanent sprayed concrete.

Further future savings could be envisaged through adoption of the Observational Method, once confidence in the SPTL method has been acquired, and through further understanding of ground-structure interaction, particularly with composite materials such as with steel fibre reinforcement. Additionally, the increased performance of state of the art sprayed concrete admixtures and equipment will reduce construction material costs and project duration.

9.3 SPTL options

Two general systems can be considered as SPTL methods. The first is a true one pass application method for small diameter tunnels, or tunnels founded in stable, dry ground conditions. The second approach is a two layer application process as shown in Figure 67, where the first sprayed concrete layer achieves tunnel stability, whilst the second layer (acting monolithically with the first) enhances durability and watertightness. This method is considered necessary for large diameter tunnels with multiple construction joints in the primary layer, and for tunnels founded beneath the water table. For both systems, the reduction of the amount of reinforcement steel is crucial, either by steel fibre replacement, or by optimisation of the tunnel profile and lining thickness. In all cases, the emphasis should be on buildability, where simplicity is the key to success, particularly with a method dependant on construction team performance.

Figure 67 illustrates the SPTL two layer method and suggests where the design emphasis should be placed for each layer. Of note is the timing of the installation of the second layer: This should be when the first layer has stabilised, and when there is no negative impact on the construction activities at the tunnel face. In some instances, it may be prudent for the construction of the first layer to be completed throughout the entire length of the tunnel before the second layer is placed.

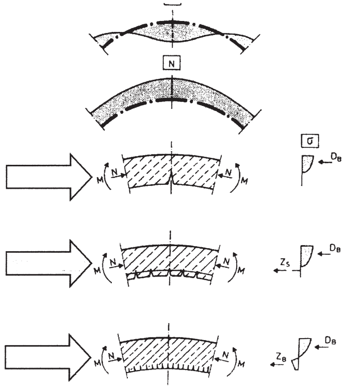


Figure 67: SPTL two layer method – cross and longitudinal section

9.4 Tunnel geometry

To reduce lining cracking to a minimum, the design should be such that the line of hoop thrust should be as close to the centre of the lining section as possible. This enables the extreme concrete stress to be kept close to the average and most of the lining's load capacity is mobilised. The role of the tunnel profile geometry is crucial in providing a means to reduce the adverse effects of bending moments, and in general, near circular geometry should be adopted, especially for the crown section of the tunnel. Bending moments produced by «flat» invert profiles may be catered for by the use of steel reinforcement installed in an in-situ concrete invert.

9.5 Lining reinforcement

9.5.1 Steel reinforcement bars and weldmesh

From experience, water ingress is associated with sections of the sprayed concrete lining that contain large diameter steel reinforcement, such as lattice girders, lattice girder connection bars, and excessive overlaps of steel weldmesh. Therefore the design emphasis should be to minimise the quantity of steel reinforcement by:

- Optimisation of the tunnel cross-sectional profile to reduce moment influences
- Increasing the thickness of the tunnel lining to maintain the line of thrust to the middle third of the concrete section
- Where structurally possible, using the more favourable option of steel fibre reinforcement.

Should mesh or bar reinforcement be required for structural reasons, it should be designed with ease of installation in mind, and evenly distributed. The reinforcement must allow full encapsulation by sprayed concrete and permit sequential installation. Under no circumstances should sprayed concrete be applied through full reinforcement cages.

9.5.2 Steel fibre reinforcement

In sprayed concrete, the use of conventional reinforcement to impart tensile capacity to the structure, such as with steel weldmesh or bars, can promote inhomogeneous structural elements due to the following:

- The need to build the required design thickness in a series of layers to encapsulate the reinforcement has a tendency to reduce the bond strength between layers.
- Corrosion of steel reinforcement can cause significant concrete spalling and cracking due to the volumetric expansion.
- Cracks produced by conventional steel reinforcement tend to be fewer, but of greater width than with fibre reinforced concrete, leading to a decrease in watertightness and durability, as illustrated in Figure 68.

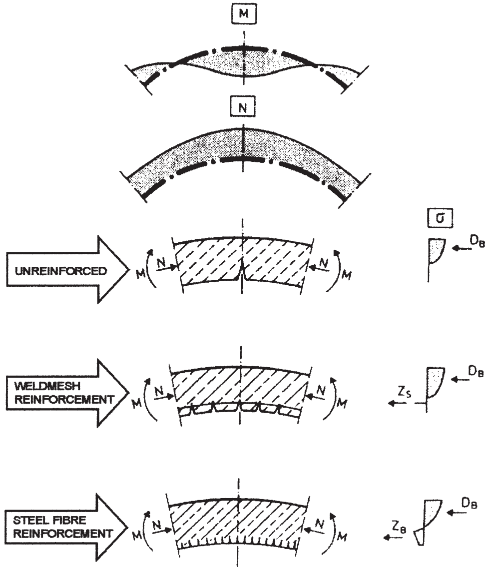


Figure 68: Cracking control through steel fibre reinforcement

Steel fibres have been used successfully in permanent sprayed concrete tunnel projects to reduce cracking widths to 0.2 mm. The advantage over conventional anti-crack reinforcement is that the fibres are randomly distributed, and discontinuous throughout the entire tunnel lining structure allowing uniform reinforcement that evenly re-distributes tensile loads, producing a greater quantity of uniformly distributed microcracks of limited depth, as illustrated in Figure 68. Steel fibres also transform the concrete from a brittle into a highly ductile material giving the lining a higher load bearing capacity, post initial cracking through the effective redistribution of load, thereby increasing the safety of the structure during construction.

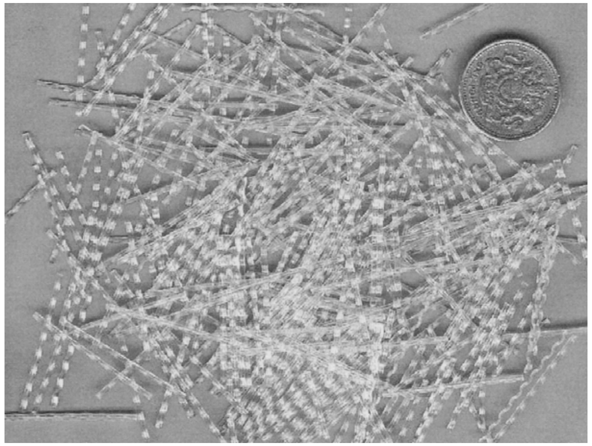


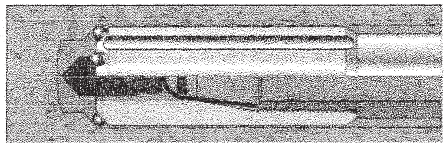
Figure 69: Polymer fibres

More recently, polymer fibres have been introduced (see Figure 69), having the added benefit of being corrosion resistant, whilst offering similar performance to steel fibres.

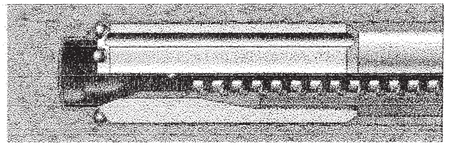
9.6 Ground reinforcement

Rockbolts, dowels and spiles should be considered as permanent supporting elements. As they are installed in the ground, there is potential for them to act as channels to groundwater and therefore, the installation should ensure that they are centred in the drill hole and fully encapsulated in grout. This achieves two functions, firstly to reduce the risk of corrosion of the bolt, and secondly to prevent water passing to the inside face of the tunnel lining.

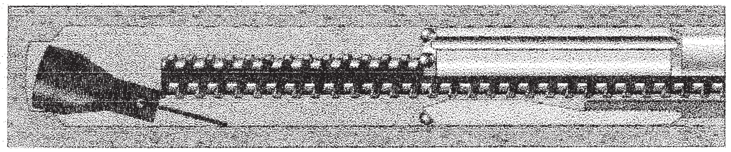
An example of a permanent rockbolt or spile is given in Figure 70, where the installation sequence of the Ground Spile Anchor (GSA) developed by the Dr Sauer Company is illustrated. The principle of the system is the boring of the hole and insertion of the rockbolt or spile in one step, being particularly beneficial in poor ground conditions that previously may have caused borehole collapse before bolt installation. Additionally, the rockbolt or spile is fully encapsulated in grout as the flushing medium is exchanged for grout approximately half a metre from the end of the borehole. The rockbolt or spile is centred in the hole by the drill rod barrel, thereby ensuring optimum corrosion protection.



Drilling with air or water flush



Installation of rockbolt towards end of drilling



Retraction of drilling barrel and injection of grout

Figure 70: GSA anchor for permanent ground support particularly in loose ground

In all grouted rockbolt (CT bolt or similar) and spile systems, the mix design of the cement grout should be geared toward the reduction of thermal cracking, and preferably to be thixotropic to prevent washout during initial setting. These grout properties can be achieved by the use of admixture products, such as MEYCO® Fix Flowcable giving a mean 28 day compressive strength of 70 MPa, chloride-free, and with little or no thermal shrinkage or cracking.

9.7 Construction joints related to excavation sequence

Figure 71 illustrates the common excavation sequences adopted for the construction of sprayed concrete lined tunnels. As stated above, the reduction of steel reinforcement from the sprayed concrete lining is one key method to significantly reduce the degree of water ingress. All joint design details require connection reinforcement from the sprayed concrete lining of one excavation sequence to the other, such as the top heading lining connection to the bench portion. Therefore to reduce the risk of water ingress, the design philosophy should be to minimise the number of joints in the tunnel lining profile, and also to simplify as far as possible the connection detail.

As can be seen from Figure 71, the top heading, bench - invert excavation sequence, with or without the initial pilot drive, offers the best solution to this problem. Of particular concern with the single and double sidewall drift methods is the complexity of the connection detail between sidewall and main tunnel lining. These joints contain lattice girders from the main and temporary sidewall, in addition to considerable connection reinforcement to provide the required structural performance of the complete profile, all exacerbating the water ingress problem. The typical location and number of such joints are indicated in Figure 71 by the black circles.

With respect to the SPTL method, where the top heading, bench - invert construction sequence is not possible due to ground stability, and a need to sub-divide the face further is required, the pilot enlargement method (Figure 71) may be regarded in favour of the sidewall drift methods.

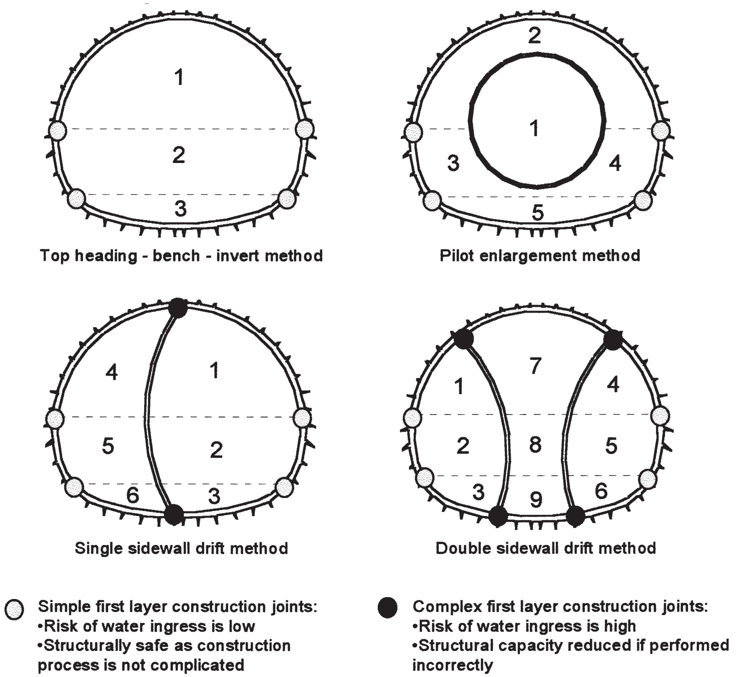


Figure 71: Joint types for sprayed concrete lined tunnel excavation methods (only joints in final lining indicated)

9.8 SPTL two layer method - second layer construction joints

The second layer of the SPTL two layer method is formed of sprayed concrete as discussed earlier. The system should have no longitudinal joints apart from the connection to the invert concrete slab. The bay lengths for the sprayed concrete lining should be approximately 4 to 5 m long as this is the typical lateral extent of a robotic spraying boom (Figure 72). The circumferential joints at the bay ends should be staggered by a minimum of 0.5 m in relation to the construction joints of the first layer to reduce the potential water path to the inside tunnel surface.

As one of the primary functions of the second layer is to produce a watertight structure, further security can be achieved by the installation of waterbars or joint sealing systems at the joint interfaces.

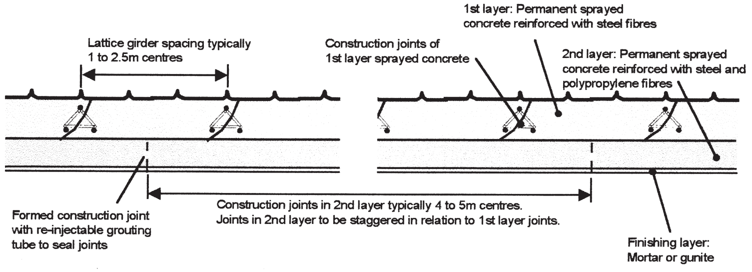


Figure 72: SPTL two layer method: 2nd layer sprayed concrete

For sprayed concrete linings, a robust system is required. An economical solution is the Masterflex® 900 - Fuko system that consists of a PVC injection tube securely fixed to a semi-circular rebate formed at the joint surface during the construction of the previous bay by means of a leading edge shutter. The Fuko tube is perforated along its length, with four neoprene strip pads covering the perforations over the entire length of the tube. These PVC pads act as one-way valves. The entire tube and pads are bound by an open webbed nylon mesh. The Fuko injection tube can be injected with either Masterflex® 601 injection resin or Rheocem® microfine cement should water ingress occur during the operational life of the tunnel. It is advisable that the first injection process occurs one year after completion of the tunnel so that any potential water paths that may establish can be identified and the respective joints targeted for treatment, rather than the unnecessary blanket injection of all joints.

The Fuko system enables re-injections to be performed during the life of the structure if required.

The injection tubes should be positioned a minimum of 50 mm from the intrados face of the tunnel lining.

9.9 SPTL two layer method - first and second layer bond

In order to provide a monolithic structure, the bond between the first and second layers must be frictionally tight and form fitting to permit the transfer of shear forces across the bond. Shear reinforcement between the two layers should be avoided as it will aid the development of water paths to the inside surface of the tunnel and a consequential reduction in durability. The shear and tensile bond between layers can be ensured by the surface roughness of the first layer to provide an effective, interlocking surface as indicated in Figure 73.

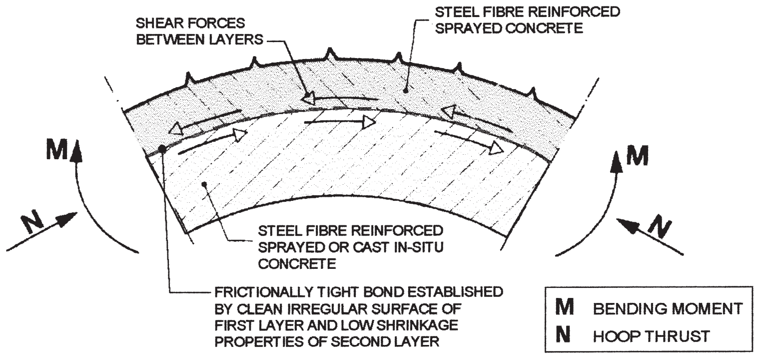


Figure 73: SPTL two layer structure indicating shear forces acting along bond interface

Additionally, the lining surface to receive the new layer should be suitably prepared following the precautions listed below.

- Removal of any damaged and disintegrated sections of the first layer
- Cleaning by high pressure air and water jetting to remove dust, soot and curing membrane applied to first layer. This is most effectively achieved using the sprayed concrete equipment
- Removal of grease or oil using a detergent

- Surfaces should be damp, not saturated, before installation of second layer.

Bond strength is also enhanced by a concrete mix design that promotes a reduction in drying and early thermal shrinkage by lowering the heat of hydration, and also by the necessary process of concrete curing. Once this bond has been achieved, the monolithic behaviour of the first layer to the second layer can occur.

To aid this structural requirement MBT have developed the concrete admixture MEYCO® TCC735. This product ensures efficient homogeneous cement hydration from the moment of spraying, and throughout the sprayed or cast in-situ layer. This internal curing action substantially reduces initial shrinkage, increases both strength and density, resulting in enhanced bonding characteristics to previous layers. A crucial benefit to the working cycle, is that the introduction of MEYCO® TCC735 to the mix design eliminates the need for external curing agents to be both applied, and removed, prior to the installation of the next layer.

9.10 Surface finish

Depending on the intended role of the tunnel structure, several surface finishes can be provided with the SPTL method varying from a sprayed concrete finish, to float finished surface.

9.10.1 Screed and float finish

Sprayed concrete linings can be surface finished by screeding and hand floating to produce a surface finish similar in quality to that of a cast in-situ lining. This process is performed on a sprayed mortar layer applied to the final structural sprayed concrete layer, and is typically 25 mm thick. Polypropylene monofilament may be included in the mix design to control surface crazing produced by thermal and surface drying effects, such as with Emaco® S88C sprayable mortar. The screeding process is relatively simple to perform using 25 mm diameter screed rails bent to the finished profile of the tunnel, and if required, further improvement to the surface finish can be attained by hand float work.

In the case of highway tunnels as shown in Figure 74, the required surface reflectance for the tunnel sidewalls up to a height of 4 m from road surface should have a smooth finish, have a high reflectance and be an average light colour. Above this zone, the crown sections of the tunnel are dark coloured and of low reflectance.

This reflectance and colour coding provides the following benefits:
- Avoids the claustrophobic effect of a reflective tube, and allows a more visual rectangular appearance, giving width to the tunnel
- A reduction in the power consumption for ventilation and luminaires
- Obscures services and hardware in the crown of the tunnel
- Provides a limit for the cleaning machine and hides a soiled appearance where the surface is not cleaned
- Aides the distribution of light onto the road surface

To achieve these surface finishes, it is recommended that the 4 m wall sections are initially screeded to the correct profile and finished by hand float work. To provide the high reflectance and light colour requirement, the application of a pigmented cementitious fairing coat such as Masterseal® 333, or an epoxy coating such as Mastertop® 1211 to the colour required is proposed. For the crown sections, the surface can be left as screeded and a similar painted treatment as above can be applied with a black pigment.

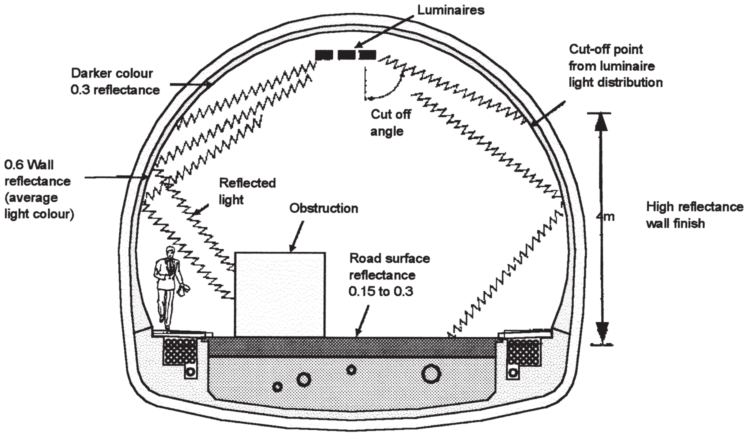


Figure 74: Surface reflectance requirements for a dual lane highway tunnel (UK)

9.10.2 Cladding systems

The alternative to the above approach to provide the required surface finish is to install sidewall cladding. Cladding systems composed of vitreous enamel on steel plate are generally acknowledged to be the most suitable for tunnel environments. Vitreous enamel (VE) cladding is durable, impact resistant, easy to clean, chemically inert and fire proof. The particular benefit of VE is that it is not a coating, but it is fused to the steel plate, forming a robust integrated surface, with a permanent colourfast finish. Such cladding systems can provide a method to screen and protect communication and electrical services, and allow a lower surface finish to be specified for the sprayed concrete tunnel linings.

9.11 Achieving sprayed concrete lining durability

The factors influencing the durability of sprayed concrete structures are dealt with in detail in chap. **6**.

9.12 Construction recommendations

9.12.1 Application requirements

Figure 75: Robotic spraying provides superior sprayed concrete quality.

To obtain a durable sprayed concrete, and to ensure that the material properties satisfy the requirements of the designer, the application process should conform to the following criteria:

- To provide a high performance concrete with minimal variance in quality.
- The system should have a controlled, pre-defined water/cement ratio of 0.45 maximum, to ensure reduced shrinkage, provide high compressive strengths and to significantly reduce permeability.

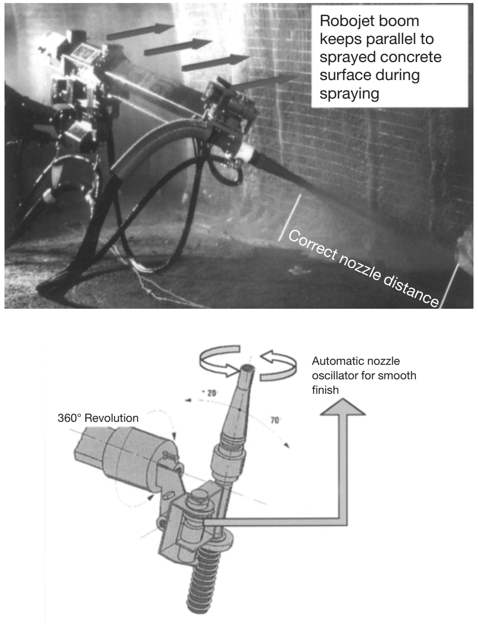


Figure 76: Robotic spraying facilitates nozzle operation.

- Thoroughly mixed (including fibres), homogenous concrete should be produced at the nozzle, and should be free from pulsation effects and blockages.
- Measured aggregate rebound should be below 10% providing the tunnel lining with a suitably graded material. This has the critical effect of reducing delaminations, shadows behind steel reinforcement, shrinkage cracking and poor microstructure.
- Measured steel fibre rebound should be less than 20% so as to provide efficient crack control and structural performance thereby imparting improved durability to the tunnel lining.

- Automated accelerator dosing unit that works in synchronisation with concrete output to allow accurate, consistent dosage rates. Dosing pumps should be capable of dispensing liquid suspensions of non caustic alkali-free accelerators.
- Thick concrete layers up to 150 mm are capable of being placed in one pass permitting a more homogenous structure.
- Low dust levels to allow greater visibility for nozzlemen to perform better control of spraying.
- The aim of the system should be to reduce the risk of human influences negatively affecting the quality of the sprayed concrete. For example, robotic spraying mobiles, such as the MEYCO® Robojet, should be used where possible, allowing superior quality sprayed concrete to be applied in a safer, more economic manner (see also chap. **10.4**).
- A ready supply of sprayed concrete should be available to apply as a contingency support when excavating the tunnel. This can be facilitated by controlling the cement hydration using Delvo®crete Stabiliser.
- In the case of loose ground and running ground water, the system should be adjustable to provide sprayed concrete with immediate setting characteristics (flash setting).
- The method of sprayed concrete application should allow effective concrete curing that will not adversely influence the bond strength between subsequent layers, such as with the incorporation of MEYCO® TCC735 concrete improving admixture.

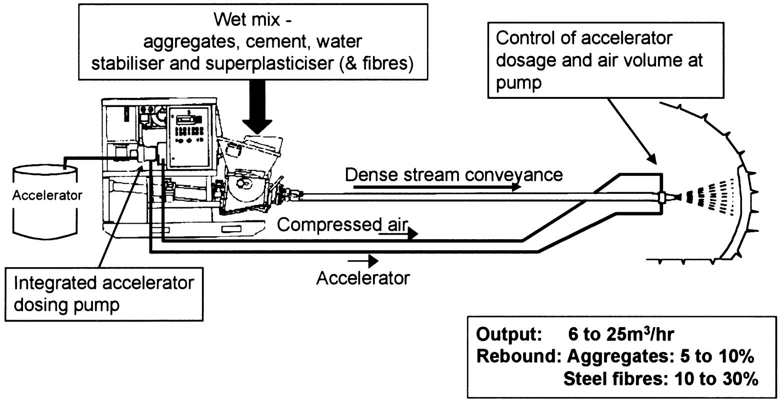


Figure 77: Wet-mix process

In view of the requirements above, it is strongly recommended that only the wet-mix sprayed concrete process be used for the construction of durable linings (Figure 77). The wet-mix process is currently the only viable method to achieve quality, particularly with respect to controlling the water-cement ratio that is vital for concrete durability and long term strength. Additionally, the wet-mix process has also demonstrated significant economical benefits over the dry-mix process.

9.12.2 Guidance on choice of modern application systems

It is strongly recommended, in view of the requirements in **9.12.1**, that only wet-mix process for sprayed concrete be used for the construction of Single Pass Tunnel Linings. This should ensure good safety, quality and productivity, leading to durable, permanent tunnel linings.

9.13 Risk management systems

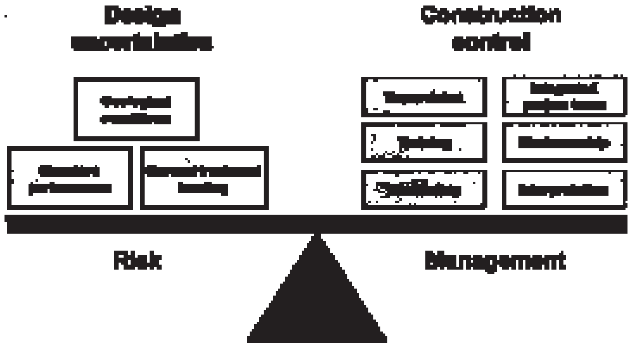


Figure 78: Simplified model to illustrate how risks associated with design uncertainties can be managed by active construction control

As with all ground engineering problems, there are inherent uncertainties in the design of tunnels, particularly where structures rely heavily on competent construction and satisfactory material performance. The design uncertainties, or risks, as simplified in Figure 78 can be summarised as follows:

- Geological uncertainties may include unpredictable changes in geology between boreholes or features not identified during the site investigation.
- Structure, or tunnel lining performance uncertainties may include inadequate sprayed concrete strength development, delayed installation or incorrect profile geometry: these are frequently attributable to human influence with sprayed concrete linings.
- Ground treatment uncertainties may be due to additional loading imposed by ground treatment operations, such as compensation grouting, particularly over fresh sprayed concrete sections of the tunnel drive. These ground treatment measures may be capable of inducing full overburden or even higher loads onto tunnel linings.

In response to these risks, the success of the SPTL method should be assured by providing a well tested risk management system during construction to provide feedback to those responsible for design, construction and supervision, permitting informed decisions to be made to reduce the possible occurrence of unplanned events. This is referred to as «construction control» in Figure 78, where the following elements are considered to be critical.

It is imperative that supervision of the works should be carried out by competent engineers who have prior experience of similar roles on similar projects. Construction and design skills developed with precast segmental tunnelling are not necessarily pertinent to sprayed concrete tunnelling practice. Particular skills required are:

- Fundamental design understanding
- Thorough construction knowledge using sprayed concrete as a permanent support system
- Knowledge of modern high performance concrete technology
- An understanding of the behaviour of the ground
- The ability to interpret deformation results from the tunnel lining and the ground monitoring
- The crucial skill of being able to communicate to the tunnel construction teams the safety critical aspects of the design and the additional need for quality and construction control

Particular emphasis should be placed on the establishment of a team relationship between all parties to the contract and any other body affected by the tunnelling works, particularly in respect of supervision and the assessment of the monitoring results. It is recommended that a technical review meeting be held each day with representatives from all parties to review all the monitoring results, sprayed concrete material properties, geological information and construction operations from the SPTL drives.

With respect to the deformation monitoring, pre-determined trigger levels should be defined in the design to forewarn of unexpected events. If these trigger levels are exceeded, pre-planned contingency measures should be available to be implemented immediately. These contingencies may range from a review of the tunnel construction sequence or an increase in the monitoring frequency, to full tunnel profile timber propping. All monitoring data should be fed back to the design team for back analysis, thereby leading to better predictions for subsequent tunnelling work, or potentially to alter the construction sequences and support requirements.

9.14 Enhancing watertightness with sprayable membranes

Although the SPTL method is based on a watertight concrete approach, added security against water ingress can be provided by the use of a waterproof membrane. Traditionally, polymer sheet membranes have been used, where the system has been shown to be sensitive to the quality of heat sealed joints and tunnel geometry, particularly at junctions. Furthermore, when sheet membranes have been installed with an inner lining of sprayed concrete, the following adverse conditions can occur:

- As the sheet membranes are point fixed, sprayed inner linings may not be in intimate contact via the membrane to the substrate. This may lead to asymmetrical loading of the tunnel lining.
- To aid the build of sprayed concrete onto sheet membranes, a layer of welded mesh is used. Due to the sheet membrane being point fixed, the quality of sprayed concrete between the mesh and the sheet membrane is often inferior, and may lead to durability concerns.
- The bond strength between sprayed concrete inner lining and sheet membrane is inadequate and leads to potential de-bonding, particularly in the crown sections of the tunnel profile.

To combat these problems, MBT have developed a water based polymer sprayable membrane, Masterseal® 340F. This sprayable membrane has excellent double-sided bond strength (0.8 to 1.3 MPa), allowing it to be used in composite structures, and also has elasticity of 80 to 140% over a wide range of temperatures. Being a water based dispersion with no hasardous components, it is safe to handle and apply in confined spaces. These material benefits of Masterseal® 340F can add significant security against water ingress when used in the following applications:

9.14.1 SPTL tunnels subject to potential occasional water ingress

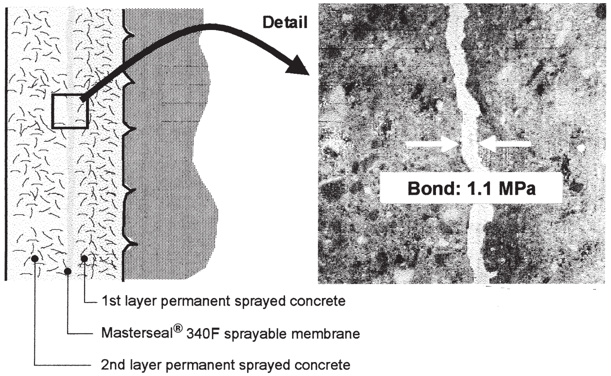


Figure 79: Masterseal® 370F sprayable membrane applied between layers of permanent sprayed concrete

For SPTL tunnels constructed above the water table, or in ground that has a low bulk permeability, Masterseal® 340F may be used as in a sandwich construction as indicated in Figure 79.

In this application, Masterseal® 340F is applied after the first layer of permanent sprayed concrete, where the sprayed surface should be as regular as possible to allow an economical application of membrane 5 to 8 mm thick. A second layer of permanent steel fibre reinforced sprayed concrete can then be applied to the inside. As the bond strength between the Masterseal® 340F and the two layers of permanent sprayed concrete is about 1 MPa, the structure can act monolithically, with the sprayable membrane resisting up to 15 bar.

As this application considers no water drainage, the 2nd layer of sprayed concrete must be designed to resist any potential hydrostatic load over the life of the structure.

9.14.2 SPTL tunnels with active water ingress

For SPTL tunnels with active water ingress and high hydrostatic loads the solution in Figure 80 may be chosen. This approach allows the collected water from behind the sprayable membrane to be relieved via a managed drainage system, typically installed in the haunches of the tunnel lining.

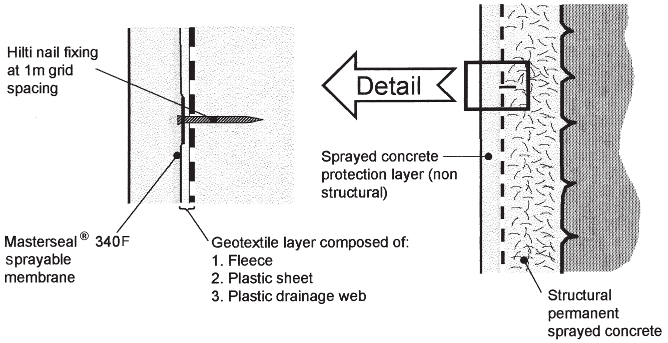


Figure 80: Masterseal® 340F applied on the inside surface of structural lining in cases of active water ingress and high hydrostatic loads

As indicated in Figure 80, the system comprises of a geotextile layer that is Hilti nail fixed to the structural sprayed concrete lining to control the water ingress and also to provide a dry surface to apply the Masterseal® 340F membrane. All geotextile joints and Hilti nail fixings are adequately covered by the Masterseal® 340F, typically with a thickness of 3 to 5 mm. A final non-structural layer of sprayed concrete is applied for protection. The thickness of the final layer of sprayed concrete is dependant on the tunnel size, can provide fire resistance and be surface finished as required.

9.14.3 Rehabilitation of existing tunnels

In many cases, sprayed concrete linings are increasingly used in the rehabilitation or upgrading of existing tunnel and underground structures. In such projects, Masterseal® 340F can offer increased protection against water ingress, and thereby enhance the durability of the new lining.

As illustrated in Figure 81, Masterseal® 340F may be applied to the existing structure directly, or with the application of a regulating layer of sprayed mortar or screeded sprayed concrete if necessary. In tunnel sections with active water ingress, the geotextile layer system (described above) applied directly to the existing structure is advised. Once the Masterseal® 340F has been applied, the permanent steel fibre reinforced sprayed concrete layer can be installed and surface finished as required.

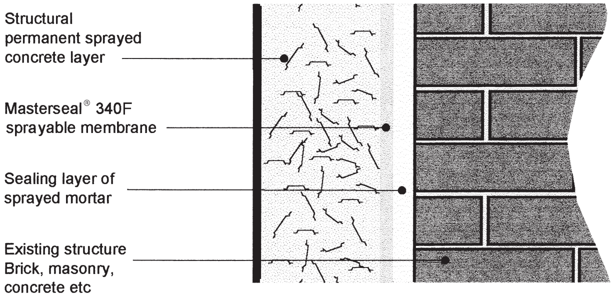


Figure 81: Masterseal® 340F applied to an existing structure as an element of rehabilitation works

10. Sprayed concrete application guideline

This chapter outlines the critical operations that need to be undertaken to achieve high quality sprayed concrete once the sprayed concrete mix design has been optimised. Amongst the operations described, one of the most essential is good nozzle technique.

With the advent of the wet-mix method, the use of robotic manipulator spraying arms has become more common place, particularly in tunnelling projects, and therefore, these methods are also reviewed. Finally, to achieve the recent, demanding requirements of achieving durable, high quality sprayed concrete structures, the need to raise levels of human competence is discussed.

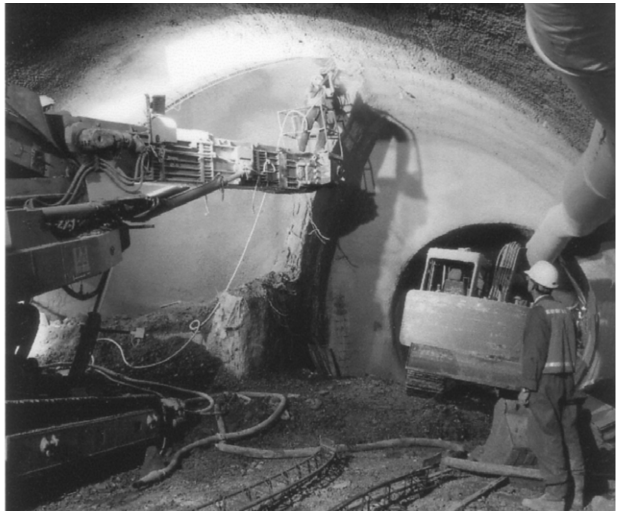
10.1 Substrate preparation

Prior to the application of sprayed concrete, the nozzleman should be aware of the required properties of the sprayed concrete lining. This may include the required thickness, profile and knowledge of any safety-critical elements of the lining that need careful attention during spraying, e.g. complex construction joints such as in the sidewall drift construction method, as indicated in Figure 82.

Immediately after excavation and before application of sprayed concrete, the exposed ground should be geologically mapped or photographed in accordance with the procedures of the tunnelling project.

For effective adhesion of the sprayed concrete to the substrate, the surface to receive the sprayed concrete should be damp and cleared of loose material by scaling and the use of compressed air and water from the nozzle. Sprayed concrete overspray from the previous advance that is loosely adhered to mesh and steel arches should also be removed.

Groundwater ingress into the tunnel will often have detrimental effects on the quality and strength of the sprayed concrete. Typically, unskilled teams will attempt to spray over active water ingress using sprayed concrete with very high accelerator dosages.



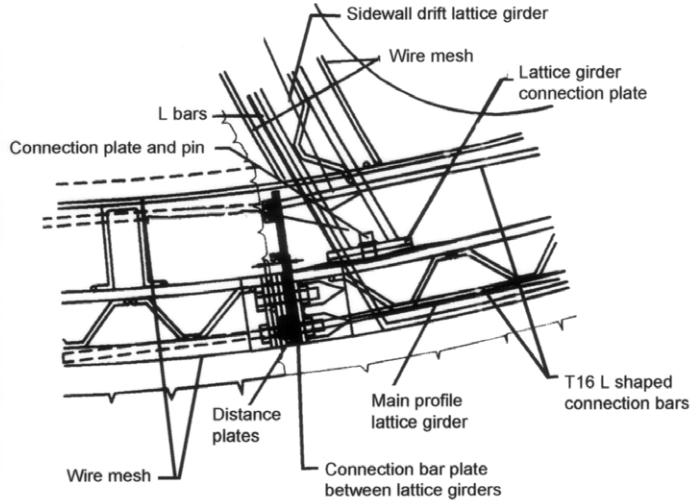


Figure 82: Sidewall drift method. Connection of temporary sidewall to main lining is typically heavily reinforced (as indicated in sketch). This joint requires good sprayed concrete compaction to ensure stability of lining after full profile constructed.

It is recommended however, that all water ingress is controlled by pre-injection or de-watering, or by managed systems such as with drainage pipes installed to capture and divert the water away to facilitate the spraying operation. These measures should be effective for at least 28 days after spraying. An example of problematic water ingress is shown in Figure 83.

Figure 83: Water ingress controlled through pre-installed pipes before application of sprayed concrete

Personal protective equipment, ventilation and lighting suitable for sprayed concrete applications are to be available at all times.

10.2 General spraying techniques

The delivered mix to the pump should be checked for batch time and for workability (wet-mix). All delivery lines from the pump to the nozzle should be securely fixed and fully lubricated with grout. If delays occur, the workability of the mix should be checked on a regular basis to determine if it is still fresh and pumpable. Under no circumstances should water be added to the mixer, or old mixes that have undergone hydration be used. The use of hydration control admixtures, such as Delvo®crete Stabiliser, is therefore recommended at all times.

With accelerated sprayed concrete mixes, it is essential not to apply sprayed concrete into the Works until it exhibits the correct setting performance. This is typically carried out by spraying directly onto the lower section of the tunnel face until the correct setting performance is observed. Furthermore, the correct air pressure and volume for the specific spraying operation should be evaluated by the nozzleman and adjusted accordingly.

One of the skills of the nozzleman is to recognise the need for applying sprayed concrete in a manner that minimises the risk of loosened blocks from falling into the tunnel work area, but also to prevent the concrete from sagging or even falling out of the crown sections. To meet this goal, the nozzleman should firstly fill all overbreaks and zones of substrate weakness, such as fissures, faults and gravel zones. The sooner this action is taken after excavation, the safer the work place.

Spraying should then commence from the lower sections moving methodically upwards to the crown. It may be prudent to increase the accelerator dosage marginally to achieve a slightly faster set, and applying numerous thinner layers rather than attempting to spray the entire thickness in one pass of the nozzle. In the crown sections of the tunnel, an initial thin layer of approximately 50 mm should be sprayed to prevent the completed sprayed lining from debonding. Subsequent layers may be built up to 150 mm in thickness.

For thick structural members, each subsequent layer should be given sufficient time to set before the next layer is applied. In large diameter tunnels this allows the spraying process to be continuous due to the relatively high surface areas and subsequent volume of concrete applied. It is good practice to apply thick sections in a series of layers, but the number should be kept to a minimum where possible. All surfaces to receive a new layer should be damp and free from loose materials.

10.3 Reducing rebound, increasing quality

One of the principal causes of poor sprayed concrete quality and increased lining costs is the amount of rebound produced during spraying. This is particularly evident in the dry-mix sprayed concrete process where the nozzleman has control over the water-cement ratio, and is responsible for the effective mixing of the concrete mix between the nozzle and the substrate. This section highlights some actions to be considered to reduce rebound and improve quality.

Figure 84 attempts to illustrate some of the major factors that can affect the degree of rebound produced by both wet and dry-mix sprayed concrete during the spraying process. In the case of the dry-mix the values given are conservative. Figure 84 assumes that the mix design, particularly the aggregate grading and water-cement ratio are optimised as described in Chapter **3**.

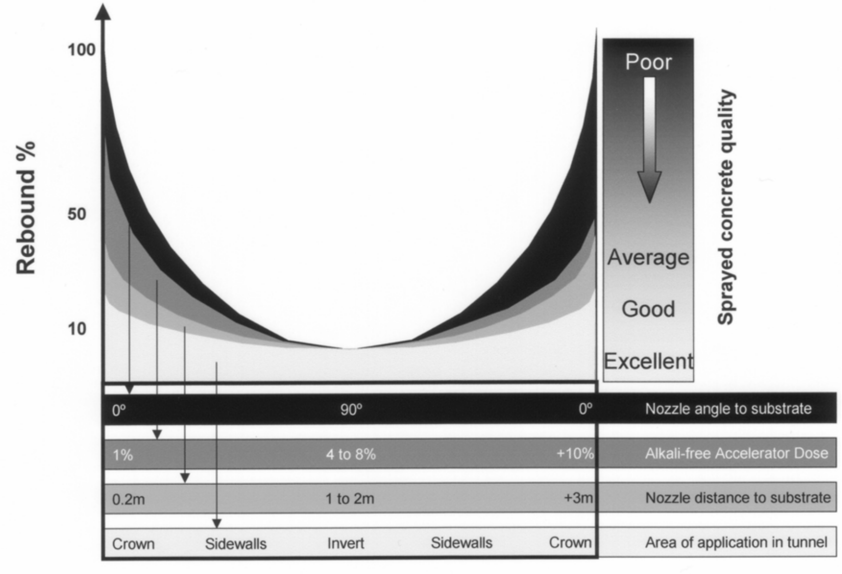


Figure 84: Effect on rebound and sprayed concrete quality of principal spraying parameters

The amount of rebound is broken down into four major factors:

- Nozzle angle to substrate
- Accelerator dosage
- Nozzle distance to substrate
- Area of application in tunnel

As indicated in Figure 84, the most significant influence on rebound is the angle of nozzle to the substrate. The nozzle should always be held at right angles (90°) to the substrate (see Figure 85) to optimise compaction and steel fibre orientation, except when full encapsulation of lattice girders and steel reinforcement is required. With hand held spraying, a perpendicular spraying angle is not always favoured by the nozzleman, as any rebounded material tends to come directly back. Even spraying angles less than 70° will cause excessive rebound values and poor compaction of the concrete. This inevitably leads to low strength and poor durability of the concrete. With more recent developments on wet-mix, robotic manipulator spraying, this problem has been mostly removed.

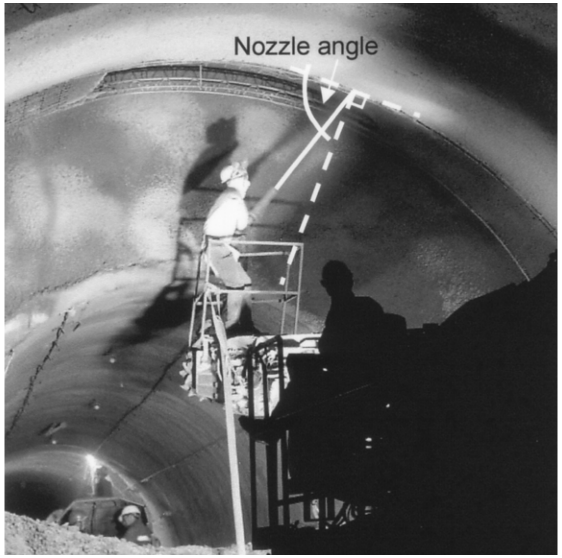


Figure 85: Nozzle angle has dramatic effect on rebound.

The distance between the nozzle and the substrate should be between 1 and 2 m, as indicated in Figure 86. If the nozzle is closer than this the projected concrete will tend to tear-off the freshly placed material. If the nozzle distance is reduced, the output should be lowered and the nozzle moved faster. Furthermore, if the nozzle distance is extended to 3 m say, then the energy to compact the concrete is severely reduced, again resulting in excessive rebound, poor compaction and low strengths. Hand held applications will tend to lower the air output to maintain the correct nozzle-substrate distance, this in turn has also detrimental effects to the quality of the sprayed concrete.

Accelerator dosage as shown in Figure 84 can also affect the degree of rebound. Too little accelerator will not provide adequate setting and strength development, so that freshly applied concrete may be «shot off» by the next pass of the nozzle as it remains too soft. By definition this is strictly not rebound, but should be avoided at all times.

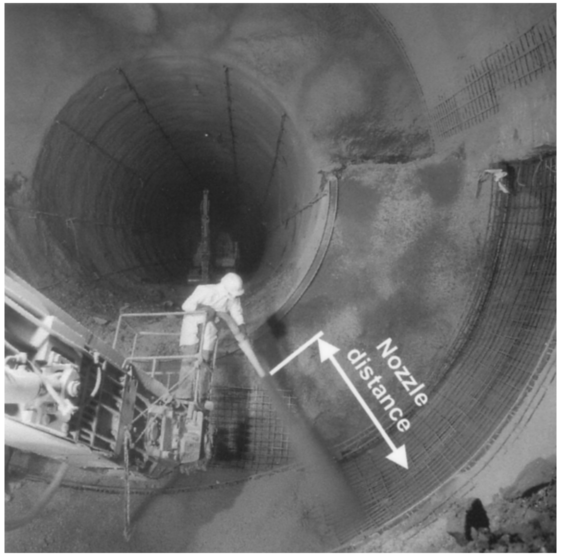


Figure 86: The distance of nozzle to substrate influences rebound and compaction.

Conversely, if the accelerator dosage is too high, for example above 10%, flash setting will create a hard surface that will cause larger aggregates to rebound, prevent complete compaction, and thereby produce reduced strength and durability of the sprayed concrete lining. For application in crown sections of tunnels, a balance between accelerator dosage for effective build rates and rebound needs to be established without compromising the required properties of the hardened concrete lining. MBT's new MEYCO® SA range of alkali-free accelerators provide a relatively low, but wide dosage range to allow fast build rates coupled with good long-term concrete performance.

Further factors that can influence the degree of rebound and hence quality of sprayed concrete are summarised as follows:

- Mesh reinforcement:
  Mesh should be securely fixed to the substrate prior to spraying. Vibrating mesh can increase rebound values considerably and cause shadows that reduce the structural capacity and long-term durability of the lining. Where possible, elect for fibre reinforced mixes for improved productivity, low rebound, enhanced structural properties, and reduced overall project costs.

  A sprayed concrete lining composed of steel reinforcement cages or bars should be systematically built-up layer by layer, and under no circumstances should sprayed concrete be applied through complete reinforcement cages.

- Air volume, pressure and delivery:
  Air volume and pressure should be those set by the manufacturer of the sprayed concrete equipment. Air bagging should be the size defined for the system, and nozzles need to be checked for wear as this detrimentally affects the output velocity of sprayed concrete. The air-accelerator injection turbo needs to be designed to optimise thorough mixing with the dense concrete stream at the nozzle.

- Nature of substrate:
  In hard rock tunnels the amount of rebound can be significantly higher than in soft ground tunnels. This is due to the contact surface being both hard and of various incidental angles to the spray direction due to the blocky nature of the rock. In such cases an initial sprayed concrete layer is advisable to act as a «cushion» to receive the structural sprayed concrete lining.

10.4 Wet-mix and robotic spraying manipulators

Many of the factors that cause high rebound values, poor compaction, loss in structural performance and hence increased project costs are attributed to the performance of the nozzleman, particularly that of the hand held nozzle systems using the dry-mix process.

The advent of modern admixtures applied to wet-mix sprayed concrete has reduced these problems significantly by enabling the placed concrete to be initially plastic in nature. For some minutes after application, new sprayed concrete can be absorbed and compacted more readily than very fast, or flash setting materials. This approach reduces rebound significantly and allows steel encapsulation to be achieved more readily.

Problems relating to nozzle angle, nozzle distance and achieving the correct compaction with the required air volume and pressure have been facilitated by the use of robotic spraying manipulators, particularly in large diameter tunnels. As shown in Figure 87, the MEYCO® Robojet spraying manipulator is controlled by a remote-control joystick operated by the nozzleman which allows spraying at the correct distance and angle at all times. This coupled with the required air volume and pressure ensures low rebound and well-compacted sprayed concrete. Good surface finishes can be achieved by selecting the automatic oscillating movement of the nozzle mode.

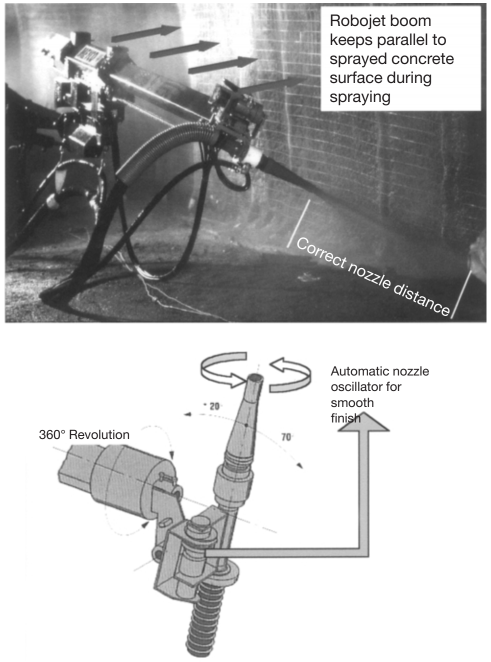


Figure 87: MEYCO® Robojet spraying manipulator - correct angle and distance for reduction in rebound and enhanced quality

New advances in spraying robots make the task of setting the optimal nozzle angle and distance even easier using the automatic mode with the MEYCO® Robojet Logica, as described in Chapter **7.2.1.1**.

10.5 Raising competence levels

Nozzlemen should have previous experience in the application of permanent sprayed concrete, and have knowledge of the sprayed concrete process to be adopted on the specific project. It is recommended that an operator be able to demonstrate his experience either as a holder of a certificate from previous work, or required to demonstrate his competence in a non-works location.

Prevailing regulations place added requirements on the people doing the spraying work to have technical knowledge of concrete, particularly with sprayed concrete. Present requirements have led to a better training of the personnel involved. The result of this is an improved quality of work. The number of special contractors who are working with sprayed concrete has increased over the last few years, which has globally raised the quality of application.

Sprayed concrete structures are heavily reliant on human competence during construction, and therefore the design should reflect this by considering the «buildability» of these structures using sprayed concrete. Designing buildability ensures that safety and durability critical elements are either designed out, or simplified for ease of construction on the job site. Furthermore, design teams should be aware of the limitations of construction processes, and be familiar with the likely material performance.

Modern sprayed concrete specifications now address the issues of achieving a quality controlled modern mix design, providing guidance on promoting durability and effective execution of the spraying processes. As an example, the new European Specification for Sprayed Concrete (1996) produced by EFNARC, provides comprehensive systems to attain permanent sprayed concrete. This specification has been the basis for new project specific specifications worldwide, and is the basis of the new European Norm Sprayed Concrete Specification. Furthermore, the EFNARC Sprayed Concrete Specification tackles issues such as nozzleman training and accreditation, and also sets out systems for contractors and specifiers to consider the structures they are building and to adapt the sprayed concrete system and mix design accordingly.

To address the international issue of sprayed concrete training, an innovative service provided by the International Centre for Geotechnics and Underground Construction, based in Switzerland, offers courses in modern sprayed concrete technology to address the shortcomings in the industry. Specific courses are available for designers and contractors, such as specialist nozzleman training for robotic spraying.

11. Time and economy

11.1 An example calculation

The main reasons for using wet mix SFRS have been given before. When evaluating economical factors, it is of decisive importance to get away from the focus on part costs like equipment investment or concrete mix materials cost. When all costs are included, experience consistently shows that substantial savings in time and money can be made on a project level. An example calculation, using experience figures, can illustrate these relations.

The basis is a 60 m^2 tunnel, 2000 m long, drill and blast excavation, 4 m round length, 100 mm theoretical sprayed concrete thickness applied per round. European cost level and Swiss Franc calculation currency. The dry-mix rebound is 30 % and the wet-mix rebound 10 %. The summary figures are shown in Figure 88.

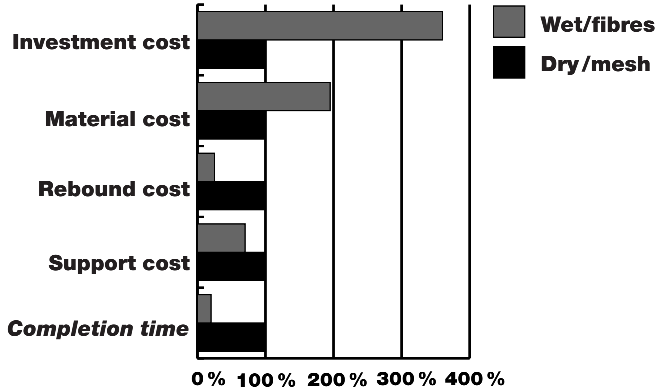


Figure 88: Comparison of wet-mix/steel fibres versus dry-mix/wire mesh

Investment cost is the value at the start of construction of the complete equipment package. Material cost means direct cost of all ingredients of the mix design, including accelerator added in the nozzle. Rebound cost contains the loss of materials, cost of extra spraying to compensate and the cost of rebound removal. Support cost means all direct cost in the sprayed concrete and reinforcement application, not including direct cost-sharing of infrastructure, administration, use of other equipment, other workers involved, delays, etc. If a cost allocation of a modest SFr. 400.– per shift hour is applied for this, the total cost of steel fibre reinforced wet-mix sprayed concrete drops to 42 % of the total cost of dry-mix sprayed concrete with wire mesh reinforcement. The main reason for this dramatic cost drop is shown at the bottom of Figure 88 (completion time): Steel fibre reinforced wet-mix sprayed concrete only needs 17 % of the time used for dry-mix spraying with wire mesh reinforcement, in order to finalise the same support volume.

Figure 88 illustrates the savings potential on the contractor's side. For the client, the potential savings are often considerably higher (earlier start-up of operation of the project). Primarily, it is therefore the client who will suffer from the consequences of non optimal solutions.

11.2 Conclusion

The wet-mix sprayed concrete technology has reached a stage of development which allows the production of high quality, durable sprayed concrete for permanent support. Further substantial technical advantages are available when reinforcement is required and steel fibres are used.

The time and cost saving potential in application of wet-mix SFRS as permanent support is in most cases substantial and sometimes dramatic. It must be ensured that the design method allows the use of such permanent support measures. Also, it must be avoided that the contract terms are counter-productive for the utilisation of modern support techniques.

Other important advantages like totally flexible logistics, very good working safety and good environmental conditions are completing the range of reasons in favour of using the wet-mix sprayed concrete technology. It is not an experiment any more, the solutions are well proven.

12. Outlook: The potential of sprayed concrete applications

Sprayed concrete is mostly used today in rock support where it has solved many difficult problems and has become a necessary aid. There is a clear tendency that more and more sprayed concrete is being applied in international tunnelling, for rock support. The total volume, in Europe alone, is more than 3 million cubic metres per year. In our opinion, this increasing trend will continue for several years to come. The actual international practices and trends could be summarized as follows:

The wet-mix sprayed concrete technology has reached a stage of development which allows the production of high quality, durable sprayed concrete for permanent support. Further substantial technical advantages are available when reinforcement is required and steel fibres are used.

The time and cost saving potential in the application of wet-mix steel fibre reinforced sprayed concrete as permanent support is in most cases substantial and sometimes dramatic. It must be ensured that the design method allows the use of these permanent support measures. Also, contract terms that are counter-productive for the utilization of modern support techniques must be avoided.

Other important advantages such as totally flexible logistics, very good working safety and good environmental conditions complete the range of reasons in favour of using wet-mix sprayed concrete technology. It is not an experiment any more, the solutions are well proven.

- The application of wet-mix sprayed concrete as compared to dry-mix sprayed concrete is dominating, with a clear trend for further increase.
- Wire mesh is still generally used for reinforcement, however, the proportion of steel fibre reinforced sprayed concrete is increasing steadily.
- There is a drive in the direction of mechanization, automation and higher capacity.
- Safety, working hygiene and environment are more focused on, and related regulations have become stricter.

- Sprayed concrete is still mostly used for temporary support, but there is an increasing interest and utilization of higher quality sprayed concrete for permanent linings.

During the last few years wet-mix sprayed concrete has also been introduced into the Mining Industry. It is a large and complex business, on the one hand imposing high safety standards to protect the miners and on the other hand requiring high productivity and output to recover the costs of extracting minerals and ores from far beneath the surface. Mining puts many difficult demands on sprayed concrete and its application, such as logistics and temperature constraints which with the use of modern admixture and equipment technologies can be overcome.

Sprayed concrete as a building method would have a much larger field of application. However, until today the degree of utilization is unfortunately still rather limited. One of the advantages of sprayed concrete is its flexibility and speed of application. Concrete which can be placed simply with a hose against form work, rock or concrete surfaces, may architecturally and constructively be varied. The only limit is the imagination and the desire for experimentation.

We therefore call upon all contractors, architects, authorities and consultants: Concrete technology, know-how, equipment and materials exist and may be mobilised to increase the range of our building activities as soon as someone plucks up courage to utilize the building method of the future: Sprayed Concrete.

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Appendix

Particular Specification
for
Sprayed Concrete

by

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Index

Introduction

This Appendix provides a modern comprehensive specification for all sprayed concrete applications both above and below ground, but excluding repair works. It should be used in its entirety, unless noted otherwise.

In accordance with modern practice, mesh reinforcement is not provided for in this Particular Specification. Steel and polymer fibre reinforcement should be used unless plain sprayed concrete is considered appropriate for a particular application.

This Particular Specification provides for three types of sprayed concrete (see «Glossary of terms» for full definitions), viz:

- Sprayed concrete Type S1:
  Fibre reinforced sprayed concrete for temporary/short term uses including immediate ground support
- Sprayed concrete Type S2:
  Fibre reinforced sprayed concrete for permanent works applications
- Sprayed concrete Type S3:
  Plain sprayed concrete for permanent works applications

This Particular Specification requires the use of wet-mix equipment for sprayed concrete Types S2 and S3 in accordance with modern practice. However, wet-mix or dry-mix equipment may be used for sprayed concrete Type S1.

Paragraph 1

Glossary of terms

Sprayed concrete
A mixture of cement, aggregate with a maximum size of 8 mm or greater and water, which may contain admixtures, projected pneumatically at high velocity from a nozzle into place to produce a dense homogeneous mass.

Plain sprayed concrete
Sprayed concrete unreinforced with either steel mesh, reinforcing bars or fibres.

Steel fibre reinforced sprayed concrete (SFRS)
Sprayed concrete which has had steel fibres added during batching, mixing or the application process as appropriate.

Sprayed concrete Type S1
SFRS which is applied as initial ground support, but is not designed to carry permanent loads. The characteristic strength of sprayed concrete Type S1 at 28 days is 45 MPa.

Sprayed concrete Type S2
SFRS which is applied as a permanent lining to carry permanent loads. The characteristic strength of sprayed concrete Type S2 at 28 days is 35 MPa.

Sprayed concrete Type S3
Plain sprayed concrete which is applied as a smoothing and/or protective layer to sprayed concrete Type S1 or bare rock, or as a surface finish to sprayed concrete Type S2 as required. The characteristic strength of sprayed concrete Type S3 at 28 days is 30 MPa.

Dry-mix process
The process of producing sprayed concrete in which a mixture of cement, aggregate, and admixtures other than accelerators when required, are weigh batched, thoroughly mixed in a dry condition and fed into a purpose made machine wherein the mixture is pressurized, metered into a dry air stream and conveyed through hoses or pipes to a nozzle immediately before which water and accelerator as a spray is introduced into the mix which is projected into place without interruption.

Wet-mix process
The process of producing sprayed concrete in which cement and aggregate are weigh batched and mixed with water and admixtures other than accelerators when required, at or near the spraying location or in mixer trucks prior to being pumped through a pipeline to a nozzle where compressed air, and accelerator if necessary, are injected and the mix projected into place without interruption.

Layer
A discrete thickness of sprayed concrete built up from a number of passes of the nozzle and allowed to set.

Rebound
Material which having passed through a spraying nozzle does not adhere to the surface to which sprayed concrete is being applied.

Base concrete
Concrete of a particular design intended for use in sprayed concrete, but which is produced without admixtures.

Admixtures
Materials added to base concrete such as accelerators, plasticizers, retarders and hydration control admixtures.

Cement
An active hydraulic binder formed by grinding clinker and complying with BS 12, BS 6588, BS 4027or BS 1370 as appropriate.

Blended cement
A hydraulic binder, manufactured by a controlled process in which Portland cement clinker or Portland cement is combined in specified proportions with a latent hydraulic binder consisting of pulverized fuel-ash (pfa) complying with BS 6588.

Microsilica concrete

Concrete manufactured in the concrete mixer by combining Portland cement complying with BS 12 or BS 4027 with a latent hydraulic binder consisting of microsilica (condensed silica fume).

Activity index for microsilica

The activity index for microsilica is the ratio (in percent) of the compressive strength of standard mortar bars, prepared with 90% cement plus 10% microsilica by mass, to the compressive strength of standard mortar bars made from cement only (Ref Norwegian Standard NS 3045).

Standard cube strength

The measured compressive strength of a cube made, cured and tested in accordance with BS 1881: Parts 1, 3 and 4.

Characteristic strength at 28 days

The value of the standard cube strength at 28 days below which 5% of the population of all possible strength measurements are expected to fall. [Characteristic strengths are quoted in this Particular Specification for the purpose of the development of mix design only, and for the information of design engineers].

***In situ* cube strength**

The notional strength of sprayed concrete at a single location, considered as the strength of a cube of sprayed concrete as it exists in the structure. [*In situ* cube strengths are given in this Particular Specification for the purpose of compliance requirements].

Base concrete

Cement

Paragraph 2

In addition to the following particular requirements cement or blended cement shall comply with BS 12, BS 6588, BS 4027 or BS 1370 as appropriate and with the Materials and Workmanship Specification for Concrete:

a) Initial setting time shall be not less than 60 minutes for strength class 42.5 and not less than 45 minutes for strength class 52.5, and not more than four hours when tested in accordance with BS EN 196: Part 3.

b) Fineness: The specific surface shall be not less than 350 m^2/kg and not more than < m^2/kg when tested in accordance with BS EN 196: Part 6. The range of results of individual test samples tested shall not be more than 40 m^2/kg.

c) Bleeding: The volume of expelled water shall not be more than 20 cm^3 when measured in accordance with *Paragraph 151*.

d) Cement in accordance with BS 12 shall be Portland cement, strength class 42.5 or strength class 52.5, and which shall comply with the following requirements:

Strength class 42.5:

Compressive strength values when tested in accordance with BS EN 196, Part 1:

- after 2 days : not less than 10 MPa
- after 28 days : not less than 42.5 MPa and not more than 62.5 MPa

Strength class 52.5:

Controlled fineness of not less than 350 m^2/kg and not more than 450 m^2/kg.

Compressive strength values when tested in accordance with BS EN 196, Part 1:

- after 2 days : not less than 20 MPa
- after 28 days : not less than 52.5 MPa and not more than 72.5 MPa

e) The temperature of the cement at the time of use in the mixing plant shall not be higher than +50°C.

f) The Contractor shall demonstrate compatibility of the cement with proposed accelerating admixtures by means of site trials to the approval of the Engineer, with particular reference to the use of non caustic alkali-free accelerators.

Latent hydraulic binders

Paragraph 3

Microsilica (condensed silica fume) is a latent hydraulic binder which shall comply with the following requirements:

a) Dry powder
  - Silica content (SiO_2) shall be not less than 85%.
  - The microsilica shall not contain more than 0.2% silica metal by mass or any deleterious materials such as quartz, rust and/or cellulose fibres.
  - Particle size shall be between 0.1 µm and 0.2 µm.
  - Fineness: The specific surface area shall not be less than 15,000 m^2/kg.
  - Total alkali content as Na_2O equivalent shall not exceed 2%.
  - Carbon content shall not exceed 2%.
  - Activity index: >95% after 28 days
  - Moisture content: <3%
  - SO_3 (water soluble): <1%

b) Microsilica/water slurry
  - pH value shall be 5.5 ±1.0.
  - Relative density shall be between 1.3 g/cm^3 and 1.4 g/cm^3.

c) Testing to establish compliance with a) and b) above shall be carried out on a monthly basis.

d) Storage and handling: Microsilica/water slurries shall be regularly agitated by circulation pumps prior to use.

e) The compatibility of microsilica and liquid admixtures shall be established by either:
  - Verification of existing test data or experience, or
  - Carrying out of appropriate accelerated testing procedures to the approval of the Engineer.

f) The optimum content of microsilica shall be determined during site trials and comply with this Particular Specification (*Paragraph 44*).

Aggregates

Paragraph 4

In addition to the requirements of this Particular Specification, aggregates for sprayed concrete shall comply with BS 882 and the Materials and Workmanship Specification for Concrete.

Paragraph 5

The nominal particle size shall be 8 mm unless approved otherwise by the Engineer.

Paragraph 6

The ten per cent fines value shall be not less than 100 kN as determined by the method specified in BS 812: Part 3:1990.

Paragraph 7

Single size aggregates shall be combined in the proportions determined during the Site Trials. The individual fractions shall be stored separately.

Paragraph 8

Coarse and fine aggregates shall be free from earth, clay loam and soft clayey shaley or decomposed stone, organic matter, friable particles and other impurities and shall be hard and dense. The grading shall be within the acceptable range and wherever possible within the target range according to the grading curve shown in Figure A.1.

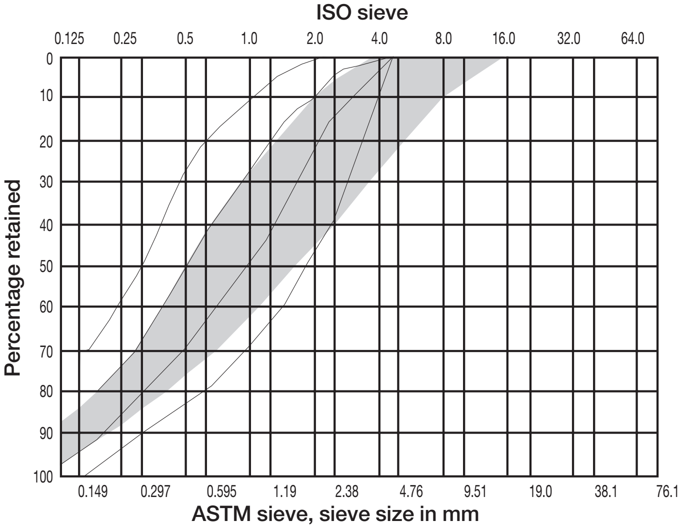

Figure A.1: Grading curve limits for sprayed concrete aggregates

Paragraph 9

The gravel fraction of the aggregate shall not exhibit excessive fragmentation during delivery. The percentage of particles smaller than 0.075 mm as determined in accordance with the washing and sieving method to BS 812: Part 103.1:1985 shall not exceed 3%.

Paragraph 10

The aggregate shall be tested for reactivity with the cementitious materials and admixtures (including accelerators) using the ASTM C1260 accelerated mortar bar method.

Paragraph 11

The grading and moisture content of the individual fractions of the aggregate shall be checked and recorded daily by the Contractor.

Paragraph 12

For dry-mix sprayed concrete the natural moisture content of the aggregate shall be as constant as reasonably practicable and shall be not more than 6%.

Water

Paragraph 13

Water shall comply with the Materials and Workmanship Specification for Concrete.

Fibres

Paragraph 14

Fibres shall be deformed steel fibres Type 1, 2 or 3 in accordance with ASTM A820:96 except that Type 1 fibres may be either circular or rectangular in section. Fibres shall be produced from mild steel or cold drawn wire and shall be ungalvanised.

Paragraph 15

Fibres may be collated with a fast-acting water-soluble glue, or may be uncollated individual fibres.

Paragraph 16

Fibres shall be stored in dry sealed containers until ready for use and shall be free from corrosion, oil, grease, chlorides and deleterious materials which may reduce the efficiency of mixing or spraying processes, or which may reduce the bond between the fibres and the sprayed concrete.

Paragraph 17

Fibres shall have an aspect ratio in the range of 30 to 150 for lengths of 12.7 to 63.5 mm. Tolerances shall be in accordance with ASTM A820:96.

Paragraph 18

Fibre type shall be selected on the basis of compliance with this Particular Specification and on suitability and ease of use in the batching, mixing and spraying processes proposed, as demonstrated by site trials to the approval of the Engineer.

Paragraph 19

Fibres which tend to form fibre balls during batching and mixing shall not be used.

Admixtures

General

Paragraph 20

In addition to the requirements of this Particular Specification admixtures shall comply with the Materials and Workmanship Specification for Concrete.

Paragraph 21

The use of admixtures for purposes not covered by the Materials and Workmanship Specification or this Particular Specification shall not be used without the written approval of the Engineer. The Contractor will be required to provide full and sufficient documentation to support the use of such materials.

Paragraph 22

Admixtures shall be free of chlorides, meaning that the percentage of chlorides shall not exceed 0.1% by weight.

Paragraph 23

The required characteristic values and consistency of delivery to the site shall be agreed in writing with the manufacturer of each admixture before commencement of spraying.

Paragraph 24

Storage conditions and usage of admixtures shall comply with the manufacturer's recommendation.

Paragraph 25

Written confirmation of the stability of admixtures with the mix water shall be obtained from the manufacturer by the Contractor prior to commencement of site trials.

Paragraph 26

Water soluble glue or other additives used to collate steel fibres shall be compatible with other sprayed concrete components. The Contractor shall provide written confirmation of this to the Engineer prior to the commencement of permanent works spraying.

Accelerators

Paragraph 27

Only liquid accelerators shall be used.

Paragraph 28

Water glass (sodium silicate) shall not be used unless in a modified polymer based form approved by the Engineer.

Paragraph 29

Only the minimum quantity of accelerator necessary shall be permitted in normal spraying operations. The quantity shall be determined by site trials, subject to maximum dosages of:

	Non caustic, alkali-free accelerators	*Aggressive accelerators*
Sprayed concrete Type S1:	10%	8%
Sprayed concrete Type S2:	8%	3%
Sprayed concrete Type S3:	8%	3%

(percentage by weight of binder)

Paragraph 30

Testing of accelerators in accordance with this Particular Specification with regard to acceleration of setting, early strength and decrease of strength at later ages (28 and 90 days), shall take place in due time before commencement of spraying.

Paragraph 31

Laboratory testing of the selected type(s) of alkali-free accelerator shall be carried out in accordance with this Particular Specification at dosages of 4 or 8% by weight of cementitious material in the base concrete, or similar dosages as recommended by the manufacturer, to establish the variability of the above properties with dosage. Accelerators showing excessive variability with dosage will not be permitted.

Paragraph 32

Accelerators shall be selected such that at the dosage chosen for use in the Works, the decrease in strength of any sprayed concrete type at an age of 28 days, compared with the base concrete without any accelerator, shall be minimised to the approval of the Engineer and in no case shall exceed 30%. Compliance with this clause shall be demonstrated by site trials to the approval of the Engineer.

Paragraph 33

Accelerators delivered to the site shall be tested in accordance with this Particular Specification not less than once every two months for their reaction with the cement used, with particular reference to the setting behaviour and strength decrease after 28 days. The stability of accelerators during storage shall be visually inspected at similar intervals. Storage times and working temperature ranges shall be in accordance with the manufacturer's recommendations. The manufacturer's safety instructions shall be observed.

Plasticizers and retarders

Paragraph 34

Plasticizers and retarders shall comply with BS 5075: Part 1 and may be used in sprayed concrete Types S1, S2 and S3 in accordance with the Materials and Workmanship Specification for Concrete, this Particular Specification and subject to the approval of the Engineer.

Paragraph 35

Plasticizers and retarders may be used to reduce the quantity of the mixing water and to improve the pumpability of the concrete. The effects and optimum dosages of plasticizers and retarders shall be determined by site trials in accordance with this Particular Specification.

Paragraph 36

Plasticizers and retarders shall be checked regularly, or as required by the Engineer, for setting time, water reduction and development of strength as compared with the base concrete.

Paragraph 37

Compatibility of plasticizers and retarders with cements, latent hydraulic binders and accelerators shall be verified by observation in the Site Trials.

Hydration control admixtures

Paragraph 38

Hydration control admixtures may be used in sprayed concrete Types S1, S2, and S3 in accordance with this Particular Specification and subject to the approval of the Engineer. Hydration control admixtures used in sprayed concrete Types S2 and S3 shall not have chemical constituents which cause a decrease in strength with age other than provided for in *Paragraph 32* of this Particular Specification.

Paragraph 39

Hydration control admixtures may be used to control the hydration of the mix as appropriate to expedite construction of the Works. The effects and optimum dosages of hydration control admixtures shall be determined by site trials in accordance with this Particular Specification.

Paragraph 40

Compatibility of hydration control admixtures with cements, latent hydraulic binders and accelerators shall be verified by observation in the Site Trials.

Paragraph 41

Hydration control admixtures shall be used in accordance with the manufacturer's instructions. Particular care shall be taken to ensure adequate mixing when used in the dry-mix process.

Particular requirements

Equipment

Paragraph 42

Sprayed concrete may be applied by either the wet-mix or dry-mix process, subject to the requirements of this Particular Specification, *Paragraph 48*.

Performance requirements

Paragraph 43

The minimum performance requirements shall be as shown in Table A.1.

Particular mix requirements

Paragraph 44

Mix designs in accordance with this Particular Specification (see *Paragraph 71*) shall comply with the particular mix requirements shown in Table A.2.

Other particular requirements

Paragraph 45

Sprayed concrete shall be capable of being applied in layers up to 100-150 mm in thickness with good adhesion to the ground or previous layers of sprayed concrete without sagging or slumping.

Paragraph 46

Sprayed concrete shall be dense and homogeneous without segregation of aggregate and/or fibre or other visible imperfections.

Paragraph 47

Sprayed concrete Type S2 shall not develop plastic shrinkage or drying shrinkage cracks of a width greater than 0.05 mm. This shall be determined by appropriate inspection and measurement techniques to the approval of the Engineer undertaken in sprayed areas greater than 10 m x 10 m applied in the Works in accordance with this Particular Specification.

Table A.1: Minimum performance requirements for sprayed concrete

Parameter		Test method or *Paragraph No*	Sprayed concrete S1	Sprayed concrete S2	Sprayed concrete S3
Characteristic *in situ* cube strength****					
Site Trials	at 1 day	BS EN 12504-1:2000	8 MPa	**	**
	at 7 days*	“	21 MPa	20 MPa	**
	at 28 days	“	35 MPa	28 MPa	25 MPa
Works Tests	at 1 day	“	8 MPa	**	**
	at 7 days*	“	21 MPa	20 MPa	**
	at 28 days	“	35 MPa	28 MPa	25 MPa
Flexural strength					
Site Trials	at 28 days	EFNARC (1996), Section 10.3	4.2 MPa	3.6 MPa	**
Works Tests	at 28 days		4.2 MPa	3.6 MPa	**
Residual strength class					
			Normal deformation class		
Site Trials	at 28 days	EFNARC (1996), Section 10.3	Class 3	Class 1	**
Works Tests	at 28 days		Class 3	Class 1	**
Bond strength to rock* **		*Paragraphs 160-166*	0.5 MPa	0.5 MPa	**
Durability/ permeability test (maximum penetration)		*Paragraphs 157-159*	**	30 mm	**
Dry density (all tests 28 days)	at 28 days	ASTM C642:97	2,275 kg/m^3	2,275 kg/m^3	2,275 kg/m^3
Boiled absorption (all tests 7 days)	at 7 days	ASTM C642:97	max. 9%	max. 8%	**
Voids volume (all tests 7 days)	at 7 days	ASTM C642:97	max. 19%	max. 17%	**
Setting time	initial set	BS EN 196-3	9 min	**	**
	final set	“	60 min	**	**

* = Tests used for indicative purposes only

** = Not measured

*** = Where the rock type affords no bond after proper cleaning and to the satisfaction of the Engineer this requirement shall not apply.

**** = The requirements assume that testing will be on drilled cores in accordance with *Paragraphs 77 a)* and *b)* or *Paragraph 125*, ie 1:1 height : diameter ratio, and include a reduction factor (0.85) to allow for the effects of in situ coring. See also *Paragraph 84* or *Paragraph 129*.

Table A.2: Particular mix requirements

Parameter	Sprayed concrete Type S1	Sprayed concrete Type S2	Sprayed concrete Type S3
Cementitious content	Portland cement Class 42.5 or 52.5 (or pfa blended cement) and microsilica	Portland cement Class 42.5 or 52.5 and microsilica	Portland cement Class 42.5 or 52.5 and microsilica
Minimum cementitious content*	400 kg/m^3	400 kg/m^3	400 kg/m^3
Maximum w**/c+s ratio	0.5	0.45	0.45
Microsilica content	5-10% (4-8% when in combination with pfa blended cement)	5-10%	5-10%
Fibres:			
Minimum tensile strength	>800 MPa	>800 MPa	***
Minimum length	25 mm	25 mm	***
Maximum length	40 mm	40 mm	***
Minimum content*	40 kg/m^3	40 kg/m^3	***

* = In the Works

** = Water shall include the liquid content of liquid admixtures.

*** = Not used

Equipment

General

Paragraph 48

Sprayed concrete Types S2 and S3 shall only be applied using the wet-mix process. Sprayed concrete Type S1 may also be applied using the dry-mix process.

Paragraph 49

All equipment used for batching and mixing of materials and the application of all types of sprayed concrete shall be of designs approved by the Engineer and shall be maintained in proper working order for the duration of excavation and lining works. Full details of all equipment to be used shall be provided to the Engineer at least 4 weeks prior to commencement of site trials. The spraying gun and ancillary equipment shall be of an adequate capacity for the volumes to be applied. A stand-by spraying system of plant and ancillary equipment shall be available for the duration of excavation operations. Air for the equipment is to be clean, dry and oil free and to be provided at the equipment at not less than the operating pressure and volume rates specified by the manufacturer.

Paragraph 50

Spraying equipment shall be capable of feeding materials at a regular rate and ejecting sprayed concrete mixes from the nozzle at velocities that will allow adherence of the materials to the surface being sprayed with a minimum of rebound and maximum adhesion and density.

Paragraph 51

Equipment shall be leak-proof with respect to all materials.

Paragraph 52

Equipment shall be thoroughly cleaned at least once per shift, or at other appropriate intervals if hydration control admixtures are used, to prevent accumulations of residual deposits.

Paragraph 53

Transport pipes consisting of hoses or pipes shall be laid straight or in gentle curves. The transport pipes shall have a uniform diameter appropriate to the mix and fibre characteristics determined by site trials, and be free of any dents or kinks between the spraying machine and the nozzle.

Paragraph 54

Equipment shall allow application of sprayed concrete to all surfaces with the nozzle at the distances from the surfaces to be sprayed in accordance with this Particular Specification.

Paragraph 55

Working areas for spraying shall be well illuminated to the approval of the Engineer. Caplamps attached to safety helmets will not be accepted as sufficient illumination. Dust pollution shall be minimised by choice of appropriate equipment and by means of additional ventilation, water sprays, and by maintaining equipment in good order. Protective clothing and dust masks shall be provided for and used by all spraying operators.

Wet-mix process

Paragraph 56

Equipment for the wet-mix process shall be set up according to the recommendations of the manufacturer.

Paragraph 57

Pumping equipment shall ensure the continuous conveyance of base concrete with minimal pulsation.

Paragraph 58

The equipment shall allow for air and water in any combination to be available for preparation of surfaces and/or cleaning of finished work in accordance with this Particular Specification.

Dry-mix process

Paragraph 59

Equipment for the dry-mix process (see *Paragraph 48*) shall be set up according to the recommendations of the manufacturer.

Paragraph 60

Equipment for the dry-mix process shall be of a design that allows sprayed concrete to be applied such that dust is not created to a larger extent than by an equivalent wet-mix process. This shall be demonstrated by site trials to the satisfaction of the Engineer.

Paragraph 61

The nozzle shall be capable of allowing full and continuous control of the quantity of water to be added as well as ensuring effective mixing of all sprayed concrete ingredients.

Automatic dosing

Paragraph 62

Dosing of admixtures by hand is not permitted.

Paragraph 63

Each machine provided for the wet-mix process shall incorporate:

a) A memory programmable control system to coordinate and control all functions of the machine including the dosing of all admixtures. The system shall be capable of printing out comprehensive records of all dosing quantities and concrete throughput.

b) An integrated proportioning unit to dispense admixtures at the required dosages as controlled by the throughput of concrete; the equipment shall be capable of delivering admixtures such that the approved dosages are dispensed to an accuracy of ±0.5% of the required dosage and shall be calibrated and operated in accordance with the manufacturer’s instructions.

Paragraph 64

Equipment provided for the dry-mix process (see *Paragraph 48*) shall incorporate integrated proportioning pumps to dispense liquid admixtures into the water supply to an accuracy of ±1% of the required dosage and shall be calibrated and operated in accordance with the manufacturer’s instructions.

Remote controlled spraying

Paragraph 65

As far as practicable all sprayed concrete shall be applied using remote controlled spraying equipment appropriate to particular applications. Manual application of wet-mix sprayed concrete shall not be permitted other than in special circumstances requiring the approval of the Engineer.

Paragraph 66

Remote controlled spraying equipment shall be provided with as long reach as possible and allow the operator to observe the nozzle at all times during spraying from a position of safety and provide the operator with full and effective control of the nozzle articulation and other functions.

Paragraph 67

The equipment shall be used, cleaned and maintained in accordance with the manufacturer’s instructions.

Acceptance testing and site trials

General

Paragraph 68

The following clauses shall be read in conjuntion with the requirements of this Particular Specification (see *Paragraph 87*, «Proficiency of operatives»).

Paragraph 69

Site trials shall be started sufficiently early to ensure that the required sprayed concrete mixes are developed and all trials completed satisfactorily by the time spraying of each sprayed concrete type commences in the Works. Spraying of any sprayed concrete type shall not commence until the relevant trials and results of laboratory tests have been completed to the satisfaction of the Engineer.

Paragraph 70

The Site Trials shall employ the equipment which will be used in the Works and the constituent materials shall be fully representative of those to be used in the Works.

Development of mix design

Paragraph 71

The mix design for each type of sprayed concrete to be used shall be developed by the Contractor in two stages:

a) Production of a suitable base concrete
b) Production of sprayed concrete from the base concrete

The target mean strength for the base concrete shall be 1.25 times the characteristic strength at 28 days for the sprayed concrete, plus a safety value of 12 MPa applied to the resulting figure.

Site trials

Paragraph 72

For each type of sprayed concrete to be used a trial mix shall be designed by the Contractor and prepared with the constituent materials in the proportions proposed for use in the Works. Sampling and testing procedures shall be in accordance with BS 1881 and BS EN 12504-1:2000. A clean dry mixer shall be used and the first batch discarded.

Paragraph 73

From the trial mix an experienced nozzleman shall prepare sufficient test panels. Each panel shall be at least 1000 x 1000 mm in size and shall be 200 mm thick. The panels shall be prepared by spraying into vertical moulds (not overhead!). Moulds shall be constructed of steel or other non-water absorbing rigid materials and shall have sides splayed outwards at 45 degrees to prevent the entrapment of rebound. The sprayed concrete in the panels shall adhere well to the backform, be properly compacted and exhibit no sagging.

Paragraph 74

Target workability values shall be determined for the wet-mix process.

Paragraph 75

The panels shall not be moved for 18 hours after spraying and shall be stored without disturbance at a temperature of +20°C ±5°C and covered by polythene sheet until the time of coring. Cores for 1, 7 and 28 day compressive strength tests shall be obtained from the panels at 1 day. The cores for 7 and 28 day strength tests shall be stored in water in accordance with BS 1881: Part 111.

Paragraph 76

Cores for permeability tests shall be obtained at 1 day and shall be wrapped in plastic sheeting that is impermeable to water and water vapour for storage until time of testing at 28 days.

Paragraph 77

Cylindrical test specimens shall be cored from each test panel and tested as listed below. Drilling and dimensions of test specimens shall be in accordance with BS EN 12504-1:2000 and the Concrete Society Technical Report No 11. Drilling of cores shall be located to avoid areas of possible rebound. No two cores to be tested at any given age shall come from the same panel. Cores to be tested at different ages (i.e. 1, 7 and/or 28 days) may come from the same panel. For each test at least one spare specimen shall be provided. The testing requirements shall be:

a) Compressive strength in spray direction after 1, 7 and 28 days on 4 cores each. The prepared test cores shall be 100 mm diameter and 100 mm long.
b) Compressive strength perpendicular to spray direction after 1, 7 and 28 days on 4 cores each. The prepared test cores, to be taken from different panels, shall be 100 mm diameter and 100 mm long.

c) The water permeability in the spray direction on 3 cores taken after 28 days in accordance with this Particular Specification (*Paragraphs 157-159*). The prepared test cores, to be taken from different panels, shall be 150 mm diameter and 120 mm long.

Paragraph 78

From each trial mix an experienced nozzleman shall prepare sufficient beams for flexural strength and toughness testing in accordance with EFNARC (1996), Section 10.3.

Paragraph 79

From each trial mix an experienced nozzleman shall prepare a test area(s) of sprayed concrete applied onto rock for the purpose of bond strength testing. The location of such areas to be agreed or directed by the Engineer.

Paragraph 80

Each cored cylinder or beam shall be marked with an appropriate reference mark and the date and time of spraying.

Paragraph 81

Testing shall be in accordance with the following methods:

Test	*Method*
Compressive strength	BS EN 12504-1:2000
Permeability	Water penetration test (*Paragraphs 157-159*)
Flexural strength	see Table A.1
Residual strength value	see Table A.1
Bond strength	see *Paragraphs 160-166*

Paragraph 82

Setting times shall be observed during the trials in accordance with BS EN 196-3:1995.

Paragraph 83

Optimum fibre content shall be determined dependent on ease of use in the batching, mixing and spraying processes proposed and from the results of the tests to determine flexural strength and residual strength class (where specified).

Paragraph 84

The compressive strength of sprayed concrete cores from test panels shall be acceptable if both the compressive strength results for samples with their axes parallel to the direction of spraying and the compressive strength results for samples with their axes perpendicular to the direction of spraying, comply with the following requirements:

a) The average strength determined from the 4 cores from a particular trial shall exceed the specified characteristic *in situ* cube strength by at least:
   2.0 N/mm^2 for 1 day strength
   3.0 N/mm^2 for 7 and 28 day strengths

b) Any individual core strength result shall not be lower than the specified characteristic *in situ* cube strength by more than:
   2.0 N/mm^2 for 1 day strength
   3.0 N/mm^2 for 7 and 28 day strengths

The compressive strength of cylinders shall be deemed to be the compressive strength of cubes provided that the requirements of *Paragraph 77 a)* and *b)* are met.

Paragraph 85

The Contractor shall carry out such other tests and trials during the period of the Site Trials as may be necessary, or instructed by the Engineer, to confirm that proposed mixes and methods meet the minimum performance requirements of this Particular Specification (see Table A.1).

Paragraph 86

The Site Trials shall be repeated if the source or quality of any of the materials or the mix proportions are required to be changed during the course of the Works.

Proficiency of operatives

Paragraph 87

Nozzlemen shall have had previous experience in the application of sprayed concrete, or shall work under the immediate supervision of the foreman or instructor with such experience. Production sprayed concrete shall be applied only by nozzlemen who have successfully demonstrated their competence and their ability to produce either plain sprayed concrete or SFRS complying in all respects with this Particular Specification. Nozzlemen shall hold certificates of competence issued by the Contractor or written evidence of previous satisfactory work indicating compliance with EFNARC Guidelines for Sprayed Concrete (1999) or ACI 506.3R:91, or with similar standards to the approval of the Engineer.

Production and transport

Batching and mixing

Paragraph 88

The individual components for the production of sprayed concrete shall be measured by weight with an automatic batching device, except that admixtures may be measured by volume. The batching accuracy shall be within ±3% for all constituents. Microsilica shall be weighed separately. The method of batching used shall ensure that the accuracy can be easily checked. All measuring equipment shall be maintained in a clean serviceable condition and shall be zeroed daily and calibrated monthly.

Paragraph 89

Mixing shall be carried out in a mixer suitable for the efficient mixing and discharge of dry or wet batched materials as appropriate.

Paragraph 90

Regular checks shall be made to ensure that complete mixing is consistently achieved. Tests for mix consistency shall be in accordance with ASTM C94 or similar approved international standards.

Paragraph 91

The addition of fibres shall be at a stage in the mixing suitable for the spraying equipment. The procedure for the addition of fibres shall be determined during the Site Trials. Fibres shall be added and mixed in a manner to avoid clumping and bending of the fibres. Any fibre clumps in the mix shall be diverted and removed by means of a screen placed over the hopper of the spraying machine. Fibres shall be uniformly distributed throughout the mortar matrix without isolated concentrations. Fibres shall not be added to the mix at a rate faster than that at which they can be blended with the other ingredients without forming balls or clumps.

Paragraph 92

The mixed base concrete for the wet-mix process shall be applied within one and a half hours. This time may be extended by the use of retarders, plasticisers or hydration control admixtures as provided for in and used in accordance with this Particular Specification.

Paragraph 93

The mixing time for the dry-mix process shall be sufficient to produce complete mixing and shall be at least 1 minute. The mixture shall be delivered by means of appropriate equipment and segregation shall be avoided.

Paragraph 94

Mixed materials for the dry-mix process may be used up to one and a half hours after the addition of cement provided that the sprayed concrete can be applied satisfactorily. Any unused material after this time shall be discarded. This period may be extended by the use of hydration control admixtures as provided for in and used in accordance with this Particular Specification.

Transport

Paragraph 95

For sprayed concrete produced by the dry-mix process, the dry mixture may be transported by truck mixers or non-agitating containers. The dry mixture shall be effectively protected against any influence of the weather.

Paragraph 96

For sprayed concrete produced by the wet-mix process, the base concrete shall be transported by truck mixers and/or concrete pumps. Remixing of material shall only be carried out with the approval of the Engineer. The mixture shall be effectively protected against any influence of the weather.

Application

Sprayed concrete application

Paragraph 97

Sprayed concrete shall not be applied to any rock or existing sprayed concrete surface without the prior approval of the Engineer which shall be in writing. The Contractor shall give an agreed period of notice to the Engineer in writing of his intentions to spray except for reasons of safety of the Works in which case the circumstances shall be reported to the Engineer without delay.

Paragraph 98

Before the application of sprayed concrete, checking and correction of the excavated cross section profile shall be carried out and rock surfaces and/or existing sprayed concrete shall be cleaned with compressed air and, as far as the local conditions permit, with an air-water mixture as necessary to remove all material which may prevent proper adhesion of the sprayed concrete to the surface. The surface to receive sprayed concrete shall be damp, but without free water prior to the application of sprayed concrete. Treatment with an air-water mixture to ensure that the surface is sufficiently clean and damp shall be done shortly before the application of sprayed concrete.

Paragraph 99

Action shall be taken to control groundwater and prevent it adversely affecting the sprayed concrete lining. Adopted measures shall be to the approval of the Engineer and remain effective for at least 28 days. Water inflows which might cause deterioration of the sprayed concrete, or prevent adherence, shall be diverted as detailed on the drawings, or otherwise proposed by the Contractor, by channels, chases, pipes or other appropriate means to the invert or to the groundwater drainage system.

Paragraph 100

Sprayed concrete shall only be applied by a nozzleman certified in accordance with this Particular Specification (see *Paragraph 87*). The distance between the nozzle and the surface to be sprayed shall not exceed 1.5 m with the wet-mix process and 2.0 m with the dry-mix process. The nozzle shall, as a general rule, be held perpendicular to the application surface except as necessary to ensure proper embedment of steelwork such as lattice girders, where shown on the drawings or otherwise directed.

Paragraph 101

Depending on the required final thickness the application of SFRS may be undertaken in two phases to minimise rebound, the first phase being a 50 mm layer.

Paragraph 102

Each layer of sprayed concrete shall be built up by making several passes of the nozzle over the working area using good working practices and nozzle manipulation. The sprayed concrete shall emerge from the nozzle in a steady and uninterrupted flow. Should the flow become intermittent for any cause the nozzleman shall direct it away from the work until it again becomes constant.

Paragraph 103

Where a layer of sprayed concrete is to be covered by succeeding layers, it shall first be allowed to set and loose material and rebound shall be removed. The surface shall be checked for soundness, repaired as specified, finally cleaned and wetted using a blast of air and water.

Paragraph 104

No rebound material shall be covered with sprayed concrete. All rebound material shall be removed from the working area and shall not be used in the Works. Disposal of rebound shall be in accordance with the Contract and with proper regard to the risks of environmental pollution.

Paragraph 105

For vertical and near vertical surfaces application shall commence at the bottom. Layer thickness shall be governed mainly by the requirement that the material shall not sag. Where thick layers are applied the top surface shall be maintained at a slope of approximately 45 degrees. For overhead surfaces sprayed concrete shall preferably be applied from the shoulder to the crown.

Paragraph 106

Pockets, sags or other defects shall be cut out and resprayed. The area of respraying shall be not less than 300 mm x 300 mm.

Paragraph 107

Finishing actions, such as trowelling or screeding, shall be avoided and may require remedial works to be undertaken.

Paragraph 108

The temperature of the mix before spraying shall not be below +5°C or above +35°C unless special provisions are made to the approval of the

Engineer. Spraying shall not be undertaken when the ambient temperature is below +5°C.

Thickness and profile control

Paragraph 109

Where specified on the drawings the minimum layer thickness shall be controlled by proprietary fluorescent plastic thickness control markers pushed into an initial sprayed concrete coating. Thickness control markers shall be used at a frequency of at least one marker per 2 m^2 of sprayed area and shall in general be located at points of maximum protrusion of the excavated surface into the tunnel void. Thickness control markers shall be removed from sprayed concrete immediately after spraying to leave open small holes through the thickness of the sprayed concrete as a permanent pressure relief provision. Detailed proposals of type, material and method of use of thickness control markers shall be submitted by the Contractor to the Engineer for his approval.

Paragraph 110

Lattice girders and/or other embedded steelwork shall be embedded by at least 30 mm of sprayed concrete Type S1.

Paragraph 111

Sprayed concrete Type S1 may follow the contours of the rock surface with appropriate rounding of edges and corners, provided that protruding blocks of sound rock still firmly part of the rock mass have a minimum sprayed concrete cover of 2/3 of the specified thickness.

Paragraph 112

The Contractor shall verify the thickness of any sprayed concrete layer by drilling 25 mm diameter percussion probe holes at any location and at an agreed time if required to do so by the Engineer. The Contractor shall provide every necessary facility to the Engineer to allow inspection of the probe holes. Inspection holes may be left open subject to the approval of the Engineer.

Paragraph 113

Control of the profile of the tunnel lining as shown on the drawings shall be by manual or electronic means to the approval of the Engineer. Laser based equipment shall comply with all necessary local health and safety legislation and shall be used in accordance with the manufacturerer's instructions.

Curing

Paragraph 114

All sprayed concrete shall be properly cured using methods and materials to the approval of the Engineer in order to limit cracking due to plastic shrinkage, early thermal contraction and long term drying shrinkage and to ensure effective bond between layers of sprayed concrete by preventing premature surface dehydration. The use of internal curing compounds shall be subject to the requirements of *Paragraphs 20-25* of this Particular Specification.

Paragraph 115

If sprayed curing agents are proposed where a further layer of sprayed concrete is to be applied site trials of the bond between layers as agreed with the Engineer shall be carried out using the approved mixes and methods of working before such agents shall be used in the Works.

Paragraph 116

Curing shall be effective within 20 minutes of completion of each spraying operation. Wet curing shall be for a minimum period of 7 days.

Paragraph 117

Sprayed concrete Type S1 need not be subject to special curing measures *unless* the sprayed concrete is to be covered by additional layers of any type and/or, in the opinion of the Engineer, the results of Works Tests indicate that the requirements of this Particular Specification are not being consistently achieved, in which cases the sprayed concrete shall be cured as for Types S2 and S3.

Works tests

General

Paragraph 118

Tests shall be carried out on a routine basis on cores or other samples taken from sprayed concrete applied in the Works. Only for certain specific tests as indicated in the following clauses shall panels or beams be prepared for test purposes.

Paragraph 119

Concrete mix control shall be carried out in accordance with the Materials and Workmanship Specification for Concrete and this Particular Specification («Test methods»).

Paragraph 120

Specimens shall be tested in accordance with the following clauses. The tests shall be carried out using the following methods:

Test	*Test method*
Compressive strength	BS EN 12504-1:2000
Flexural strength*	EFNARC (1996), Section 10.3
Residual strength value*	EFNARC (1996), Section 10.3
Bond strength	See *Paragraphs 160-166*
Durability/permeability	See *Paragraphs 157-159*
Dry density	ASTM C642:97
Boiled absorption	ASTM C642:97
Voids volume	ASTM C642:97
Setting time	EFNARC (1996), Appendix 1, Sect. 4.2
Fibre content*	See *Paragraphs 141-143*
Fibres*	See *Paragraph 156*
Workability*	BS 1881: Part 102

* = Only with SFRS

Paragraph 121

The frequency of carrying out each test for mix control shall be in accordance with the Materials and Workmanship Specification for Concrete and for carrying out of tests on specimens taken from sprayed concrete placed in the Works as given in the following clauses of this Particular Specification.

Paragraph 122

The dimensions of test specimens shall be as specified in this Particular Specification («Acceptance testing and site trials»).

Paragraph 123

The location of specimens to be taken from the Works shall be proposed by the Contractor and approved by the Engineer. Test results will not be acceptable unless this clause is fully complied with.

Paragraph 124

Where the nominal required sprayed concrete thickness is less than 100 mm the cores for compressive strength or other testing requiring specimens longer than 100 mm shall be taken from areas where the actual thickness is greater than 100 mm. Alternatively additional sprayed concrete thickness shall be applied in selected areas proposed by the Contractor and approved by the Engineer for subsequent coring of test specimens.

Compressive strength test

Paragraph 125

Compressive strength tests shall be carried out on prepared test cores measuring 100 mm in diameter and 100 mm in length taken from sprayed concrete in the Works in accordance with BS EN 12504-1:2000 and the Concrete Society Technical Report No 11. The time of coring shall be as close as possible to 24 hours after placing. Cores required for 28 day strength tests shall be obtained at the same time as those for 1 and/or 7 day tests and stored in the laboratory in accordance with BS 1881: Part 111.

Paragraph 126

The frequency of coring shall be such as to obtain 3 cores each for 1 day and 7 day strength for sprayed concrete Type S1, and 28 day strength for all sprayed concrete, for every 100 m^3 of each sprayed concrete type used in the Works. Depending on the compliance of test results with this Particular Specification, circumstances of application and importance of construction, the frequency may be reduced to every 200 m^3 or increased to every 50 m^3 as approved or directed by the Engineer. The cores shall be cored through the whole thickness of the sprayed concrete and visually inspected to verify that the sprayed concrete is dense and homogeneous without segregation of aggregate and/or fibre or other visible imperfections.

Paragraph 127

Tests for 1 day strength shall be carried out at 24 hours ±2 hours and for 7 day and 28 day strengths in accordance with BS 1881: Part 120.

Paragraph 128

Instead of testing cores taken from sprayed concrete placed in the Works, indirect test methods to the approval of the Engineer may be used to determine the 1 day strength of sprayed concrete Type S1, but shall not be used for testing of any other sprayed concrete type. Results of indirect tests shall be correlated to the 1 day *in situ* compressive strengths to the satisfaction of the Engineer during site trials.

Paragraph 129

The strength of sprayed concrete measured by cores taken from the Works (or by indirect test methods in accordance with *Paragraph 128*) shall be acceptable if the compressive strength results comply with the minimum performance requirements set out in Table A.1.

One test result shall consist of the mean of 3 core strengths. 7 day results shall be used for indicative purposes only.

The compressive strength of cylinders shall be deemed to be the *in situ* compressive strength of cubes provided that the requirements of *Paragraph 125* in terms of core diameter and height/diameter ratio are met.

Flexural strength and residual strength class tests

Paragraph 130

Tests to determine flexural strength and residual strength class shall be determined from tests on beams cut from panels sprayed in the vertical position. The test method shall be EFNARC (1996), Section 10.3. Panels shall be sprayed at the time of Works production using moulds of steel or other non-water absorbing rigid materials measuring 1000 mm x 1000 mm x 200 mm deep with sides splayed outwards at 45 degrees to prevent the entrapment of rebound. Spraying technique, thickness of layers and the operator shall all be the same as for production spraying.

Paragraph 131

Panels shall be clearly marked to identify the time, date and location of spraying. Panels shall not be moved for 18 hours after spraying. Panels shall be cured and protected as approved by the Engineer. Beams shall be sawn from the panels in accordance with the test method (EFNARC (1996), Section 10.3). The top of the beams shall be orientated as the tension face in the test rig and the top face shall not be sawn.

Paragraph 132

The frequency of testing shall be one test (meaning the average of tests on 3 beams from the same panel(s)) for each 300 m^3 of each type of SFRS placed in the Works.

Paragraph 133

Sprayed concrete shall be acceptable if the results for flexural strength and residual strength value exceed the minimum requirements of this Particular Specification with no single value of flexural strength being lower than 75% of the average result for each test and no single test beam having a stress/deflection curve which falls below the next lower residual strength class (with the exception of beams specified for Class 1).

Bond test

Paragraph 134

The frequency of bond testing shall be one test (meaning the average of tests on 6 specimens from the same general area of the Works as approved by the Engineer) for each 500 m^3 of each type of sprayed concrete applied directly to rock surfaces.

Paragraph 135

The sprayed concrete shall be acceptable if the results for one test exceed the minimum requirements of this Particular Specification and 5 out of 6 of the individual values exceed 50% of the specified minimum requirement.

Durability/permeability test

Paragraph 136

The frequency of durability/permeability tests shall be one test (meaning the average of tests at 28 days on 3 cores taken from sprayed concrete in the same general area of the Works as approved by the Engineer) for each 500 m^3 of sprayed concrete Type S2 applied in the Works.

Paragraph 137

The sprayed concrete shall be acceptable if the average results for one test are less than the specified maximum depth of water penetration and no individual result exceeds 50 mm depth of penetration.

Dry density, boiled absorption and voids volume

Paragraph 138

Dry density, boiled absorption and voids volume shall be determined for sprayed concrete sampled from the Works. Material sampled for other purposes may be used subject to the approval of the Engineer.

Paragraph 139

The frequency of testing shall be one of each type of test (meaning the average of tests on 3 specimens taken from 7 and 28 days old sprayed concrete, as required, in the same general area of the Works as approved by the Engineer) for each 200 m^3 of sprayed concrete Type S1 or S2 applied in the Works.

Paragraph 140

The sprayed concrete shall be acceptable if the average results for each test comply with the specified requirements.

Fibre content

Paragraph 141

An evaluation of fibre content shall be carried out on a 5 kg specimen of fresh SFRS sampled from the Works immediately after spraying. After washing out, the steel fibres shall be collected, dried and weighed. The weight shall be compared to the volume of the specimen which shall be determined as approved by the Engineer (EFNARC (1996), Section 10.9).

Paragraph 142

The frequency of testing for fibre content shall be one test (meaning the average of tests on 3 specimens) for each 200 m^3 of SFRS applied in the Works.

Paragraph 143

The sprayed concrete shall be acceptable if the average results for one test exceed the specified minimum requirements and no individual result is less than the specified minimum by more than 20%.

Testing of fibres

Paragraph 144

At least one tensile test, consisting of 10 randomly selected finished fibres, shall be performed for each 4.5 tonnes of material supplied or each shipment if less than 4.5 tonnes. The average value of tensile strength in these tests shall not be less than the specified minimum. The tensile strength of any one of the ten specimens shall not be less than 800 MPa.

Paragraph 145

Bending tests of fibres shall be in accordance with ASTM A820:96.

Paragraph 146

Rejection and retest requirements shall be in accordance with ASTM A820:96.

Workability test

Paragraph 147

The workability of SFRS shall be measured by slump tests to BS 1881: Part 102 after the addition of fibre and plasticiser to the required dosages. Samples shall be tested for every 50 m^3 produced.

Failure to comply

Paragraph 148

Should the results of any Works Test not comply with the acceptance criteria set out in the foregoing clauses of this Particular Specification, the results and test procedures shall first be checked and confirmed. The Engineer shall, if necessary, require that additional tests be carried out by the Contractor to determine the extent of the non-compliance and/or new mix proportions or methods determined to avoid further such failures.

Paragraph 149

If the Engineer considers that the indicated non-compliance(s) may reduce unacceptably the long term stability or serviceability of the Works and/or are detrimental to the effectiveness of the Works, the Contractor shall as instructed by the Engineer either:

a) Remove the defective sprayed concrete in strips or panels in such a way that the safety of the Works and persons is not endangered and replace with sprayed concrete that is acceptable, or;
b) Apply an additional layer of sprayed concrete not exceeding the thickness originally required and to be determined by the nature of the non-compliance.

Test methods

General

Paragraph 150

Tests required by this Particular Specification shall be carried out using methods which shall be in accordance with the specified standard(s) unless specified otherwise in the following clauses.

Bleeding of cement

Paragraph 151

The method for determining the extent of bleeding of cement shall be as follows:

a) Pour exactly 98 g of water with a temperature of +20°C into a 250 ml glass beaker with a small magnetic stirring rod. At medium stirring rate add 115 g of cement steadily within a period of 20 seconds. Stir the mixture for 2 minutes until a homogeneous, relatively thin cement paste (water cement ratio = 0.85) has been achieved.
b) Transfer the homogenized mass into a 100 ml measuring cylinder up to the 100 ml index mark by means of a glass rod (do not pour directly into cylinder). The measuring cylinder shall be placed in a high glass beaker filled with water maintained at +20°C ±2°C during the entire period of testing.
c) After 120 minutes the amount of cement that has settled shall be read from the scale, i.e. the amount of supernatant water may be determined. The reading in millilitres corresponds to the percentage by volume of expelled water.

Testing of accelerators

Setting time of aluminate based accelerators

Paragraph 152

1) 30-32 g of water
2) 100 g of cement (+20°C ±1°C)
3) Mix for 2-3 min. until a homogeneous cement paste is obtained.
4) Add 6 g of the aluminate accelerator to be used.
5) Mix intensively by hand for a maximum of 15 seconds so that the accelerator is well distributed into the cement paste.

   Remark: Do not mix for more than 15 seconds, or it will spoil the setting characteristics.
6) Form a cake out of the accelerated cement paste and put it under the vicat test machine.
7) Only use the manual (not automatic) Vicat needle machine.
8) Test the initial set and record it. The needle should stop at 1–2 mm from the bottom.
9) Test the end of set and record it. The needle may not penetrate into the cement paste.

Interpretation of results:

Initial set	<30 sec	<60 sec	>60 sec
Final set	<3 min	<4 min	>4 min
Rating	good	acceptable	not acceptable

Main criteria for aluminate based accelerators:

C_3A	5–10%, preferably 7–9%
Blaine	>3500, preferably >4000

Also depending on the blending of fly-ash, slag and gypsum.

Setting time of alkali-free accelerators in liquid form

Paragraph 153

Alkali-free liquid accelerators are sensitive to the type of cement: With some cements too slow setting characteristics are obtained. The sensitivity to cement is limited to the wet-mix application. In dry-mix spraying the negative impact of the setting characteristics can be compensated by lowering the w/c ratio.

Therefore, the reactivity/setting time with the cement type(s) used in the project have to be checked.

In a cement paste:

(Equipment: mixing pot with rounded spatula, manual Vicat needle, stopwatch, testing cups)

1) 26-35 g of water
2) 1 g of superplasticizer
3) 100 g of cement (+20°C ±1°C)
4) Mix very intensively until a homogeneous paste is obtained
5) Add 3-10 g of accelerator and mix for max. 5 sec
6) Immediately after mixing: fill up a test cup, place it under the manual Vicat needle and start measuring the penetration

7) Record initial set (needle stops 1-2 mm from the bottom of the cement mouse)
8) Record final set (needle cannot penetrate into the cement mouse)

Interpretation of results:

Initial set	<2 min	<4 min	>4 min
Final set	<5 min	<8 min	>8 min
Rating	good	acceptable	not acceptable

In a mortar (according to EN 196-1):

(Equipment: Hobbart mixer, manual Vicat needle, mortar prism forms)

1) Pour 195 g of water into the mixer, add 2-6 g of plasticizer and 450 g of cement (+20°C ±1°C) and stir for 30 sec
2) Add 1350 g of norm sand and mix for 30 sec
3) Mix at medium speed for 30 sec
4) Stop for 90 sec
5) Mix again for 30 sec
6) Check the flow of the mortar (according to EN 196-1). Required flow: 15-18 cm. Adjust by adding water, if necessary
7) Add accelerator and mix for max. 15 sec
8) Immediately after mixing: prepare the test prism
9) Fill the prism form on a vibration table to avoid bad compaction
10) Place it under the manual Vicat needle and start measuring the penetration
11) Record initial set (needle stops 1-2 mm from the bottom of the cement mouse)
12) Record final set (needle cannot penetrate into the cement mouse)
13) Measure the compressive strength at 6 hours and at 24 hours

Interpretation of results:

Initial set	<2 min	2-5 min	>5 min
Final set	<6 min	8-13 min	>13 min
6-hour strength	2.5-4 MPa	1-2.5 MPa	<1 MPa
24-hour strength	18-25 MPa	10-18 MPa	<10 MPa
Rating	good	acceptable	not acceptable

Note:
If the setting times are bad, the 24-hour strength can still be good. Even with a slow setting it is possible to spray 5–7 cm on the wall or 3–5 cm overhead.

In most instances these tests do not work very well as the «gel» time is too fast for thorough mixing. MBT have developed a Viper test equipment to spray mortars for setting tests as a consequence.

Strength decrease

Paragraph 154

Decrease in strength resulting from the use of accelerators shall be determined according to the following procedure:

a) Mortar cubes shall be used in accordance with BS 4550: Part 3: Section 3.4.
b) A comparison of the 7-day and 28-day strengths of mortar shall be carried out in accordance with the methods specified in the following clauses of this Particular Specification as follows:
   Strength shall be determined without the accelerator (A)
   Strength shall be determined with the accelerator at the dosage determined by the setting time tests (B)
c) Permissible maximum strength reduction:

$$\frac{A - B}{A} \times 100$$

   shall be not more than the specified maximum percentage.

Mortar test (without accelerator, basic mortar mix)

Paragraph 155

The compressive strength of mortar cubes without accelerator shall be determined in accordance with BS 4550: Part 3: Section 3.4:1978, Item 2 except that the following mix ratio shall be used:

570 g	cement (+20°C ±1°C)
1710 g	sand (according to the requirements of BS 4550: Part 6)
370 g	water

Testing of fibres

Paragraph 156

Tests on steel fibres shall be in accordance with ASTM A820:96 except that the cross sectional area used to compute the tensile strength shall be carried out to four decimal places, in units of square millimetres, and shall be:

a) For drawn wire fibres, the area calculated from the actual diameter of the parent source material or finished fibres.
b) For cut sheet fibres, the area calculated from the actual thickness and width of the parent source specimen, or if fibres are tested, the area of each individual fibre calculated from the measured length and weight of the fibre, weighed to the nearest 0.0001 g, based on a density of 7,850 kg/m^3.
c) For melt-extraction fibres, the area calculated from the equivalent diameter of the fibres, computed from measured average length and the weight of a known quantity of fibres, based on a density of 7,850 kg/m^3.

Durability/permeability test

Paragraph 157

The durability/permeability test shall take the form of a water penetration test in accordance with DIN 1048: Part 5 and the following clauses.

Paragraph 158

Three 150 mm diameter cores shall be obtained by rotary diamond drilling from each site trial in accordance with *Paragraphs 76* and *77* and from the Works Tests in accordance with *Paragraphs 136* and *137*. The cores shall be of sufficient length to allow test specimens to be prepared which shall be 120 mm in length for testing in accordance with the specified standard.

Paragraph 159

For each core the following information shall be recorded:

- Date of coring
- Core number
- Direction of spray

Testing of bond strength

Paragraph 160

Testing of the strength of the bond between sprayed concrete and rock shall be carried out either by *in situ* testing or by testing of rock/sprayed concrete bonded cores in a laboratory.

Paragraph 161

The apparatus to carry out the tests and detailed test methods shall be as described by EFNARC (1996), Section 10.6 or otherwise as approved by the Engineer.

Paragraph 162

Tests shall be carried out on cores greater than 60 mm and less than or equal to 100 mm in diameter. Drilling for *in situ* testing must penetrate the rock by at least 15 mm.

Paragraph 163

Cores taken for laboratory testing shall be cured and protected until the time of testing.

Paragraph 164

The rate of loading shall be greater than 1 MPa per minute and less than 3 MPa per minute.

Paragraph 165

The following information shall be recorded:

- Specimen identification, sprayed concrete type and source
- Specimen dimensions
- Age at testing and curing conditions
- Rate of loading and deformation
- Maximum load and calculated bond strength
- Description of failure including the fracture surface

Paragraph 166

Tests may be terminated if the calculated bond strength exceeds 1.5 MPa.

Paragraph 167

Particular references and standards

The following is a list of the standards referred to in this Particular Specification for Sprayed Concrete.

The Contractor may propose for the Engineer's approval the adoption of alternative standards, in which case he shall provide comprehensive details and explanations with his proposal and copies, in English, of any relevant standards. The Contractor shall allow for the time necessary for review and approval of such alternative(s) by the Engineer.

BS 12:1996	**Specification for Portland Cement**
BS 812	**Testing Aggregates**
Part 2:1995	Methods for determination of physical properties
Part 3:1990	Methods for determination of mechanical properties
Part 100:1990	General requirements for apparatus and calibration [Replaced by BS EN 932-5:2000]
Part 101:1984	Guide to sampling and testing aggregates
Part 102:1989	Methods for sampling [Replaced by BS EN 932-1:1997]
Part 103	Method for determination of particle size distribution
Section 103.1:1985	Sieve tests
Section 103.2:1989	Sedimentation test
Part 105	Methods for the determination of particle shape
Section 105.1:1985	Flakiness index
Section 105.2:1990	Elongation index of coarse aggregate
Part 106:1985	Method for the determination of shell content
Part 109:1990	Methods for the determination of moisture content [Partially replaced by BS EN 1097-5:1999]
Part 110:1990	Methods for the determination of aggregate crushing value [Partially replaced by BS EN 1097-2:1998]
Part 111:1990	Determination of ten per cent fines value [Partially replaced by BS EN 1097-2:1998]
Part 112:1990	Method for the determination of aggregate impact value [Partially replaced by BS EN 1097-2:1998]
Part 113:1990	Method for the determination of aggregate abrasion value [Replaced by BS EN 1097-8:2000]
Part 114:1989	Method for determination of polished stone value [Replaced by BS EN 1097-8:2000]
Part 117:1988	Method for determination of water-soluble chloride salts
Part 118:1988	Method for the determination of sulphate content
Part 119:1985	Method for the determination of acid-soluble material in fine aggregate
Part 120:1989	Method for the testing and classifying drying shrinkage of aggregates for concrete
Part 121:1989	Method for the determination of soundness
BS 882:1992	**Specification for Aggregates from Natural Sources for Concrete**
BS 1370:1979	**Specification for Low Heat Portland Cement**
BS 1881	**Testing Concrete**
Part 101:1983	Method of sampling fresh concrete on site [Replaced by BS EN 12350-1:2000]
Part 102:1983	Method for determination of slump [Replaced by BS EN 12350-2:2000]
Part 108:1983	Method for making test cubes from concrete [Replaced by BS EN 12390-1:2000]

Part 111:1983	Method of normal curing of test specimens (+20°C method) [Replaced by BS EN 12390-1:2000]
Part 112:1983	Methods of accelerated curing of test cubes
Part 114:1983	Methods for determination of density of hardened concrete [Replaced by BS EN 12390-7:2000]
Part 115:1986	Specification for compression testing machines for concrete [Replaced by BS EN 12390-4:2000]
Part 116:1983	Method for determination of compressive strength of concrete cubes
Part 120:1983	Method for determination of compressive strength of concrete cores
Part 124:1988	Methods for analysis of hardened concrete
Part 125:1986	Methods for mixing and sampling fresh concrete in the laboratory
Part 127:1990	Method of verifying the performance of concrete cube compression machine using the comparative cube test
Part 131:1998	Methods for testing cement in a reference concrete
Part 201:1986	Guide to the use of non-destructive methods of test for hardened concrete
Part 202:1986	Recommendations for surface hardness testing by rebound hammer
Part 203:1986	Recommendations for measurement of velocity of ultrasonic pulses in concrete
Part 204:1988	Recommendations on the use of electromagnetic cover meters
Part 205:1986	Recommendations for radiography of concrete
Part 206:1986	Recommendations for the determination of strain in concrete
Part 207:1992	Recommendations for the assessment of concrete strength by near-to-surface tests

BS 4027:1996	**Specification for Sulphate-Resisting Portland Cement**

BS 4550	**Methods for Testing Cement**
Part 3	Physical tests
Section 3.4:1978	Strength tests [Replaced by BS EN 196-1:1995 and partially by BS 1881-131:1998]
Section 3.8	Test for heat of hydration
Part 6:1978	Standard sand for mortar cubes

BS 5075-1:1982	**Specification for Accelerating Admixtures, Retarding Admixtures and Water Reducing Admixtures [Partially replaced by BS EN 480 and BS EN 934]**

BS 5328	**Concrete**
Part 3:1990	Specification for the procedures to be used in producing and transporting concrete
Part 4:1990	Specification for the procedures to be used in sampling, testing and assessing compliance of concrete

BS 6588:1996	**Specification for Portland Pulverised Fuel Ash Cement**

BS EN 196	**Methods of Testing Cement**
Part 1:1995	Determination of strength
Part 2:1995	Chemical analysis of cement
Part 3:1995	Determination of setting time and soundness
Part 6:1992	Determination of fineness
Part 7:1992	Methods of taking and preparing samples of cement
Part 21:1992	Determination of chloride, carbon dioxide and alkali content of cement

BS EN 480	**Admixtures for Concrete, Mortar and Grout. Test Methods**
Part 1:1998	Reference concrete and reference mortar for testing
Part 2:1997	Determination of setting time
Part 4:1997	Determination of bleeding of concrete
Part 5:1997	Determinaton of capillary absorption
Part 6:1997	Infrared analysis
Part 8:1997	Determination of the conventional dry material content
Part 10:1997	Determination of water-soluble chloride content
Part 11:1999	Determination of air void characteristics in hardened concrete
Part 12:1998	Determination of the alkali content of admixtures

BS EN 932	**Tests for General Properties of Aggregates**
Part 1:1997	Methods for sampling
Part 5:2000	Common equipment and calibration

BS EN 934	**Admixtures for Concrete, Mortar and Grout. Concrete Admixtures**
Part 2:1998	Definitions and requirements
Part 6:2000	Sampling, conformity control, evaluation of conformity, marking and labelling

BS EN 1097	**Tests for Mechanical and Physical Properties of Aggregates**
Part 2:1998	Methods for the determination of resistance to fragmentation
Part 5:1999	Determination of the water content by drying in a ventilated oven
Part 8:2000	Determinaton of the polished stone value

BS EN 1367	**Tests for Thermal and Weathering Properties of Aggregates**
Part 4:1998	Determination of drying shrinkage

BS EN 12350	**Testing Fresh Concrete**
Part 1:2000	Sampling
Part 2:2000	Slump test

BS EN 12390	**Testing Hardened Concrete**
Part 1:2000	Shape, dimensions and other requirements for specimens and moulds
Part 4:2000	Compressive strength. Specification for testing machines
Part 7:2000	Density of hardened concrete

BS EN 12504 Testing Concrete in Structures
Part 1:2000 Cored specimens. Taking, examining and testing in compression

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ASTM C94 Standard Specification for Ready Mixed Concrete

ASTM C642-97 Standard Test Method for Specific Gravity, Absorption and Voids in Hardened Concrete

ASTM C1018-97 Standard Test Method for Flexural Toughness and First Crack Strength of Fibre Reinforced Concrete (Using Beam with Third Point Loading)

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