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Construction Chemicals

Modern Advances and Applications of Sprayed Concrete

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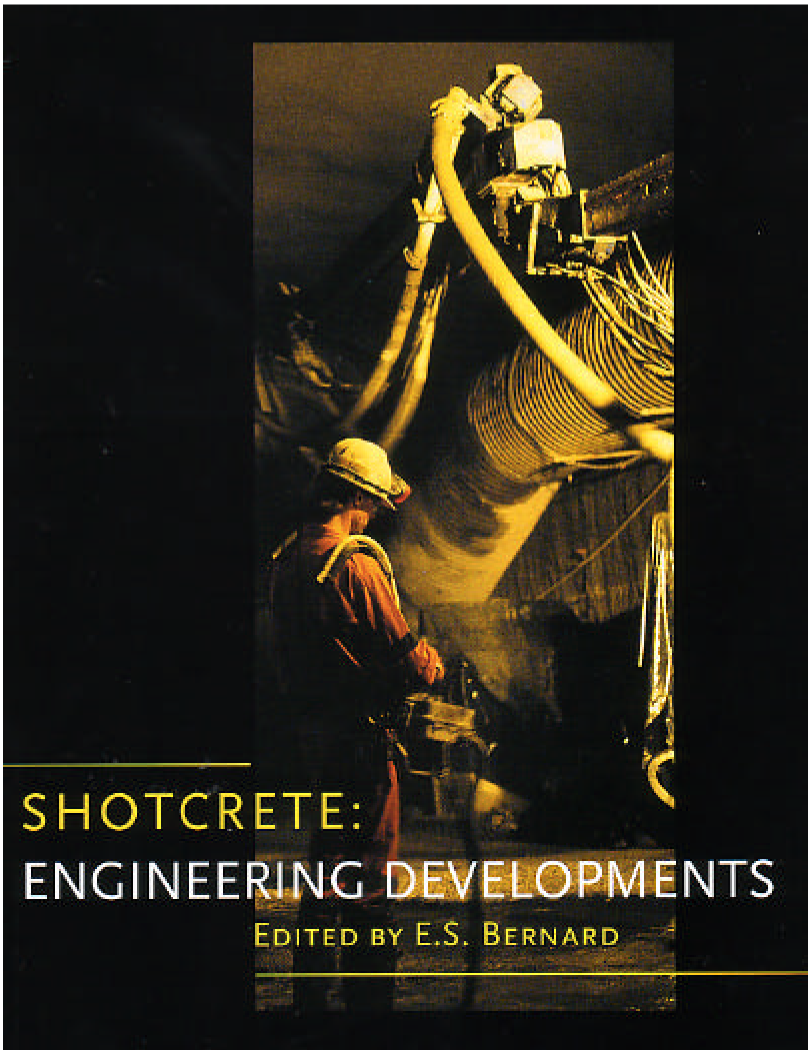

Keynote paper given at the International Conference on Engineering Developments in Shotcrete, Hobart, Tasmania, Australia, 2nd to 4th April 2001

Building Tomorrow Together

UNDERGROUND

Modern Advances and Applications of Sprayed Concrete

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ABSTRACT: The purpose of this paper is to give an overview of modern sprayed concrete systems, but also to highlight that sprayed concrete should be regarded as concrete. To achieve this, the paper describes the rapid evolution of sprayed concrete and the international trends that have developed in the last ten years. Recent developments in the application systems are explored, particularly pertaining to the use of modern, high performance admixtures and accelerators to ensure high quality, environmentally safe sprayed concrete, produced in line with recognised conventional concrete practices. Coupled with the mix design technology, new, more automated sprayed concrete equipment are reviewed that enable high production rates whilst reducing the risk of less negative human influences on quality. Finally, the paper discusses new developments of sprayed concrete and additional applications outside the underground construction industry that demonstrates sprayed concrete a versatile permanent civil engineering material.

1 INTRODUCTION

Concrete can be considered as the most cost-effective, versatile building material, and when used with steel reinforcement, virtually all structural elements, even complex shapes can be formed. As conventional concrete is placed in its fluid state, there are often significant costs associated with the necessary shutters and formwork to hold the concrete in position whilst it sets and hardens. Sprayed concrete addresses this drawback by being able to be placed by spraying concrete to a required structural geometry facilitated by the fast setting characteristics of the concrete mix, negating the need for shutters.

Sprayed concrete or gunite is not a new invention. Sprayed concrete has been known for more than 90 years. The first sprayed concrete jobs were done in the United States by the Cement Gun Company Allentown as early as 1907, with the sprayed concrete product named “gunite” using simple to operate, compressed air driven pumps, similar to that in Figure 1. Gunite was, and in some circumstances today refers to a fine-grained (sand), mortar concrete. Today, the terms “Sprayed concrete” and “Shotcrete” are commonly used, and are normally based on larger aggregate mixes (maximum 8 to 16mm). The term “Shotcrete” is used widely in the USA, and “Sprayed concrete” is more typically used in Europe, but gaining rapid acceptance in other regions of the world.

For the purposes of this paper, and in order to avoid confusion, the EFNARC European Specification for Sprayed Concrete define the expression “Sprayed Concrete” as a mixture of cement, aggregate and water projected pneumatically from a nozzle into place to produce a dense homogeneous mass. Later, this term will also be employed in the new European Norms and Standard for Sprayed Concrete (CEN) which is currently under preparation.

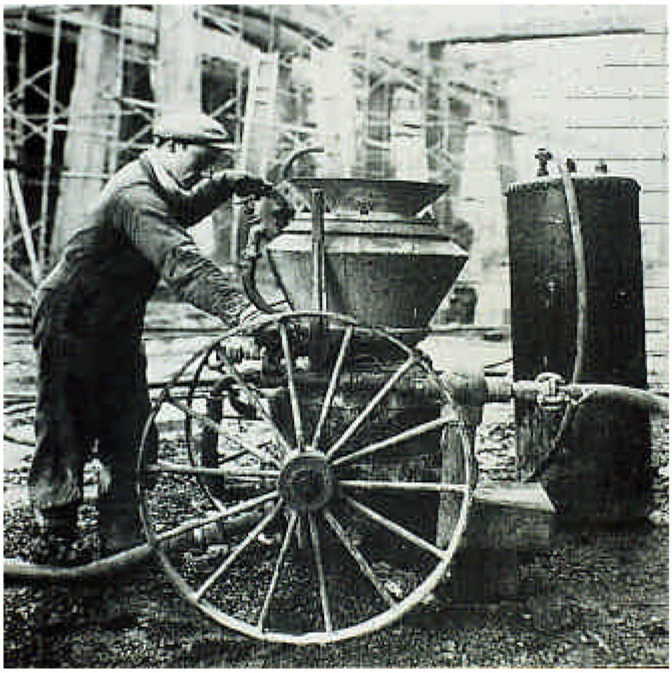


Figure 1: Traditional dry-mix gunite pump

In recent years the use of sprayed concrete has equipped the modern underground construction industry in particular with a fast, cost effective lining system. Recent technological developments with the mix design and application equipment described in this paper have occurred as a result of the demands of this industry. Regional differences in the adoption of new sprayed concrete technology vary considerably in both field of application and geographical location.

2 SPRAYED CONCRETE PROCESSES AND INTERNATIONAL TRENDS

Approximately 30 years ago, the only method available for the application of sprayed concrete was via the dry-mix process. This remained the dominant method until the mid nineties, when eventually the wet-mix process began to be used more widely. Currently the wet-mix method is being adopted on a worldwide basis as the preferred choice, particularly for ground support works. The following sections briefly describe the two processes, and offers –some explanations to the geographical and application spread of the two systems.

2.1 *Dry-mix process*

The dry-mix process is a technique in which the cement and aggregate are batched either at a site-based plant or pre-batched and kiln dried into silos or bags. This material is fed into a dry-mix sprayed concrete pump, similar to that shown in Figure 2, and delivered to the nozzle by compressed air. At the nozzle, the water necessary for hydration is added to the discretion of the nozzleman.

Accelerators may be added in powder form at the pump hopper, or as a liquid with the water at the nozzle. In recent years, such as in Austria, the use of highly reactive cement in a pre-blended mix has replaced the need for accelerators, however these products must be stored in extremely dry conditions prior to use.

Figure 2: Typical dry-mix sprayed concrete pump

The dry-mix system's virtues are that it is a simple system, with few mechanical and mix design issues that can go wrong. It is often these two factors that have been the reason for selection of the dry-mix process in the past.

However, every process has its drawbacks. With the dry-mix method these an be described as:

- High costs of wear and tear on gaskets and friction discs on rotor machines.
- The environmental and safety impact of the high concentrations of dust generated from the system must be taken into account.
- Another important problem in dry spraying is rebound. Depending on the application surface rebound can be expected to exceed 15% and be as high as 35 or 40%. Typically the range is 20 to 25%. Rebound can be considerable reduced by the use of new kinds of additives and admixtures such as microsilica or the Delvocrete Hydration Control system. The average losses can be restricted to an average of 15% in these cases.
- Low equipment performance is another drawback often cited. Currently, machines are available which are capable of more than 10 m³/hour, but this is not possible by manual application methods; a spraying manipulator is required. However, due to the increase in wear costs, outputs above 8 m³/hour become critical from an economical point of view. A typical output of between 4 and 6m^3/hr should be considered.
- In quality control terms, the sprayed concrete material properties produced by the dry-mix process have a great degree of variance due to inadequate mixing between the nozzle and the substrate, unknown and variable water-cement ratios, and possibly pre-hydration of the delivered mix to the pump.
- Taking the above into account, it is understandable that sprayed concrete produced by the dry-mix method is considered "temporary support" in the tunnelling industry.

Due in no small part to the many years experience with the dry spraying process there is now a great deal of know-how available. It is extremely important that the materials, equipment and application techniques are selected to give the best possible results with regards to quality and economy.

Even though dry spraying is the older of the two technologies, because of on-going developments in machine and material technology it has been possible to continually extend the field of application. In the future it is expected that the dry spraying process will continue to play an important role. Main applications will be for projects with relatively small volumes and/or very flexible requirements such as concrete repair, which is considered the strongest market for the dry-mix process. Additional, long conveying distances suit the dry-mix process, and is consequently the method remains in use in many mine workings worldwide.

2.2 *Wet-mix process*

Similar to ordinary concrete a ready-mixed concrete from a concrete batching plant is used. 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 (thick stream transport). Today, piston pumps are dominating the wet-mix sprayed concrete pump market. A typical wet-mix piston pump is illustrated in Figure 3.

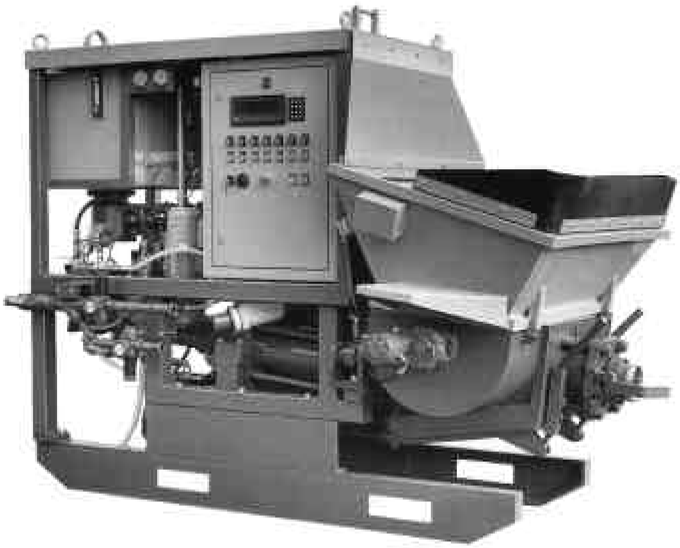


Figure 3: Modern day wet-mix sprayed concrete pump with integrated accelerator dosing system

At the nozzle, 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 robotic manipulator (see Figure 4). The air is added to increase the speed of the concrete so that good compaction is achieved as well as adherence to the substrate or surface. A mistake often made with the wet spraying is that not enough air is being used. In most cases only 4 - 8 m3/min. are added which gives a bad result in compressive strength, bond and rebound. For robot spraying, a minimum of 12 m^3/min. is required. In addition to the air, liquid set accelerators are added at the nozzle to provide fast setting, high build characteristics.

The advantages of the wet-mix are:

- low aggregate rebound 5 - 10%. Additionally, if fibres are used, the rebound values are minimal compared to the dry-mix process
- better working environment, low dust
- thick layers because of effective use of admixing material
- controlled w/c ratio (down to 0.37) and subsequent durability benefits. This leads to the concrete being considered as a permanent element of the structure
- quality variance is minimised by virtue of the material being pre-mixed and significantly reduced negative influence of the nozzleman
- higher capacity output from 4 to 25m^3/hr. Typically robotic manipulator spraying will be between 15 and 20m^3/hr
- use of steel/synthetic fibres and new advanced admixtures/additives are made possible
- Reduction in number of operatives
- better total economy on applied sprayed concrete

Figure 4: Robotic manipulator for safe, high output and quality wet-mix sprayed concrete application

The disadvantages of the wet-mix are:

- limited conveying distance (max. 300 m)
- higher demands to mix design
- cleaning costs (can be solved with the use of hydration control admixtures)
- limited open time/workability (can be solved by using hydration control admixtures)
- If not site batching, reliance on local batching plants to dose specific types and volumes of admixtures, and provide higher level of quality control during batching

2.3 *Current and future trends*

Until the mid 1990's, dry-mix spraying had been the dominating method of applying sprayed concrete. However, in view of the benefits listed above for the wet-mix system, many contractors involved with projects requiring large volumes of sprayed concrete, moved to the wet-mix process. In general, the majority of these projects were for tunnel construction and ground support works.

In view of the data presented in Table 1, the present situation worldwide is that 70 to 80% of the sprayed concrete is being applied by the wet-mix method and with a rapidly increasing tendency. In some areas, the wet-mix method has been dominant for 20 years (e.g. Scandinavia, Italy, Switzerland with almost 100% wet-mix), and it is in general, these countries that have exported the technology on an international basis. Within the next five years the wet-mix method is anticipated to represent more than 80 to 90% of all sprayed concrete works worldwide. Today, more than 8 million m3 of sprayed concrete is being applied every year; this is also set to increase as the material is used in more applications.

Table 1: Recent world trends in sprayed concrete volumes and application processes (approximate)

Country/region	Dry %	Wet %	m^3/year	Tendency
Australasia	0	100	> 50,000	wet
Italy	0	100	700,000	wet
Scandinavia	0	100	250,000	wet
France	10	90	250,000	wet
Japan	10	90	2-3M	wet
Switzerland	10	90	300,000	wet
UK	10	90	> 50,000	wet
Asia/Pacific	20	80	> 1M	wet
Brazil	20	80	400,000	wet
Germany	20	80	500,000 to 1M	wet very recently
India/Nepal	20	80	300,000	wet (large projects)
Spain	20	80	300,000	wet
Greece	30	70	200,000	wet
Hong Kong	30	70	100,000	wet
Colombia	40	60	200,000	wet
Rest of Latin America	40	60	> 300,000	wet
China	60	40	> 1M	wet (large projects)
USA	70	30	500,000	wet
Austria	80	20	250,000	wet – slow change

A brief review of the sprayed concrete development in Scandinavia and why it happened will illustrate why countries such as Italy, Switzerland, France, UK, Spain, Greece, Australia, Korea, Brazil and some other European countries have been moving in the same direction.

Between 1971 and 1980, the sprayed concrete application in Norwegian tunnelling turned from dry-mix method only to 100% wet-mix. A similar change took place in Sweden and Finland.

The next dramatic change was from mesh reinforcement to the incorporation of steel fibres. Again, the fastest adoption of new technology happened in Norway.

During the same period a similar change from manual hand spraying techniques to robotic manipulator arm application took place. Since 1976 to 1978 steel fibres and microsilica have been added to wet-mix sprayed concrete in rapidly increasing volumes.

It is not unfair to say that the Norwegian led the way into real wet-mix sprayed concrete. They are those who have definitely the most experience and who know most about wet spraying in large volumes.

The data presented in Table 1 is only an estimate but still reasonably correct and can be used for the purpose of showing today's situation and tendencies. Some comments are given as a supplement:

When the construction period started in London Underground for the Jubilee Line Extension, Heathrow Express Rail Link and other well known projects in the area, the market was practically using 100% dry-mix sprayed concrete. Within slightly more than a year this was turned around to wet-mix after one project demonstrated the significant programme and cost savings of using the wet-mix system. This is illustrated very well by the fact that MBT Intl. UGC had alone 17 MEYCO® Suprema wet-mix pumps in operation at any one time in London during 1994 to 1996.

Sometimes it is also commented or claimed that in the "Developing World" countries only the simple, low cost dry-mix method can work properly. The reality is different since there is no relation between the choice of method, local development tendency and such popular regional tags. This is well illustrated by the figures in Table 1 for China, Brazil, Colombia, and India/Nepal compared to Austria. It is suggested that an explanation as to the strength of the wet-mix method in such countries be based on the international contractors that are active on the large projects, and consequently importing the wet-mix technology.

Austria and partly Germany have been traditionally very strong dry-mix areas as Switzerland was some years ago. Switzerland converted to wet-mix in less than two years whilst Austria and Germany in particular, have developed new systems within the dry-mix method, using extremely quick setting cement types (without gypsum). This allows spraying of thick layers in one go without the use of any admixtures or accelerators.

This new alternative with quick setting cement appears to be favorable at first sight because of lower material costs per m^3 mixed. But there are some serious negative aspects to be considered, such as high rebound (> 30%), dust (above all national limits), sensitivity to cement quality, high to very high energy cost, low capacity, complicated equipment and difficult handling of the material as well as being labour intensive. Furthermore, there is no realistic chance of using steel fibres because of high fibre rebound (50 - 70%).

There are clear signs that a change in the direction of the wet-mix method will happen in Austria, as recently Germany has switched in the last year to the wet-mix method. Some first large-scale projects have been completed successfully with the wet-mix method both in Germany and Austria (Königshainer Berge, Ditschhardt Tunnel, Irlahüll-Ingolstadt - Highspeed Link with 400.000 m^3, Sieberg Tunnel, Blisadona Tunnel, Austria).

Another interesting area is Australia. Here the mining led the civil construction industry in switching from dry to wet-mix and also partly to steel fibre reinforcement. This has led to a substantially increased market share to almost 100% for wet-mix in both mining and civil construction works in Australia (e.g. Paseminco mine, Melbourne City Link).

It is clear that considering the rapid trend from dry to wet-mix sprayed concrete, the future developments within the industry will be centred on the wet-mix process. This development will inevitably have its main focus on high performance admixtures and more mechanised spraying technologies, but perhaps will also need an improvement in human aspects, such as appropriate design and specification for permanent sprayed concrete structures and education of the new technologies to operatives.

The following sections deal with the state-of-the-art wet-mix technology available today, and considers potential future developments.

3 SPRAYED CONCRETE MIX DESIGN

As with traditional methods of casting, sprayed concrete also needs to comply with traditional concrete good practice. All usual demands on the concrete technology (such as w/c ratio, amount of cement, correct consistency and curing) have to be complied with. The reason why so much poor quality concrete has been applied in many parts of the world is because it seems to be forgotten that spraying concrete is only a way of casting and that all concrete technological requirements still have to be fulfilled, such as a low w/c ratio and good workability.

Available aids to obtain good quality sprayed concrete with the wet-mix method are:

- cement
- microsilica/additives
- aggregates
- admixtures
- set accelerators
- curing
- fibres
- correct equipment
- correct execution

3.1 *Cement type and quality*

A wet-mix concrete needs a minimum of 200 - 210 litres of water to maintain workability and to avoid slump loss. In order to keep the w/c ratio below 0.45, a minimum binder content of about 450kg is needed (200 litres/0.45 = 444kg binder).

It is possible to spray with a lower cement or binder content but this will result in a high w/c ratio > 0.5, reduced quality, lower early and final strength. Furthermore, a lower binder content also increases the rebound dramatically as indicated in Figure 5. The plot demonstrates that a cement content of 450kg dramatically reduces rebound to that of below 400kg.

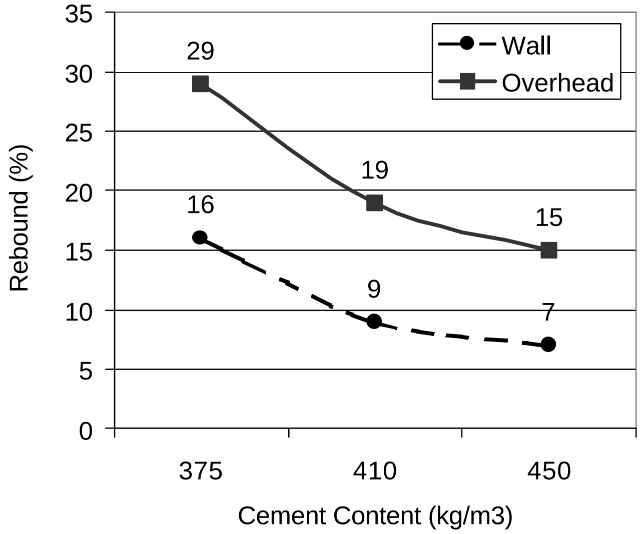


Figure 5: Plot demonstrating rebound reduction through cement increase

It is wrong to push the binder content as low as 400 kg and even less as is often attempted for economical reasons. This action is self-defeating, as the in-situ sprayed concrete is much more expensive due to the following reasons:

- higher rebound (7.5 SFR/m^3 extra costs in rebound compared to higher binder content of 450kg/m^3 because the extra rebound costs have to be calculated as well and not only the costs from the applied concrete)
- higher consumption of set accelerators because of a higher w/c ratio (1 - 2% => 4 - 8 kg/m^3 at 1 SFR/m^3)
- lower production because of more problems with consistency and more volume to spray because of higher rebound volumes

Considering these points, it is easy to understand that it is commercially prudent to add 50kg more cement/binder in order to get better economy, quality and problem-free sprayed concrete. The costs for 50kg of cement are approx. 0.12 SFR/kg x 50kg = 6 SFR/m^3, compared to extra rebound costs which are considerably higher.

It is recommended to use a cement type 42.5 or 52.5 because of the better reactivity with set accelerators, better early and final strength results and lower accelerator consumption.

Cement replacements are often considered for use with sprayed concrete mix designs, and their advised maximum quantities are given in Table 2. It should be noted however, that testing of the mix in both fresh and hardened states should be undertaken to evaluate any detrimental effects of cement replacement.

Table 2: Maximum additions of cement replacement products (EFNARC 1996)

Cement replacement material	Maximum addition
Silica fume (microsilica)	15% of Portland cement
Fly ash	30% of Portland cement
	15% of Portland/Fly ash cement
	20% of Portland/ Blastfurnace slag cement
GGBS	30% of Portland cement

3.1.1 *Cement reactivity*

One of the key factors that determine the successful application of sprayed concrete for tunnel linings is the cement-accelerator reactivity. It is essential for testing of cement-accelerator mortars to be carried out with all locally available cements to establish the best setting characteristics and strength development prior to site trials.

Although complying with national cement specifications, not all cement types are suitable for sprayed concrete works as they can prove to be incompatible with certain accelerators, giving poor setting characteristics.

The fineness, chemical composition and age of the cement essentially govern this variation in cement-accelerator reactivity. As a general guide, fineness should be above 350m^2/kg and preferably 400m^2/kg (fineness is measured in accordance with BS4550: Part 3: Section 3.3: 1978, or Blaine method ASTM 204-84). A C_3A content of not less than 5%, and preferably between 7 and 9%, is also recommended. It is always good practice with sprayed concrete applications to use fresh cement.

For guidance, typical accelerator types, dosages and setting times (Vicat needle) for sprayed concrete are listed in Table 3.

Table 3: Dosage and setting times for sprayed concrete accelerators

Accelerator	Typical dosage range	Initial set	Final set
Alkali-free liquid	4 to 10%	< 4mins	< 8mins
Modified silicates	2 to 10%	Too fast to record	< 60mins (at 6% max.)

The recent arrival of high performance alkali-free accelerators with extremely fast gelling and setting times has effectively ruled out the use of the standard vicat test from being performed as often the 15 second mixing time destroys the gel. To address this MBT are currently examining new laboratory testing methods that allow analysis of the new alkali-free accelerators and have attempted to reflect more realistically the actual sprayed concrete process that occurs on site.

3.2 *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. This leads to a concrete with reduced permeability, increased sulphate resistance and improved freeze-thaw 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, the latter benefit above is of paramount importance. Details are given below.

3.2.1 *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 favorable from a technical point of view to use 5 - 10% (by cement weight) 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 a high rate of plasticisers/ superplasticisers to disperse the microsilica. The dosage of admixture increases by approximately 20%, compared to sprayed concrete without microsilica.

3.3 *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 it's 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 viscous 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. Using more cement or microsilica will compensate too little fine material. Increasing the dosage of water-reducing admixtures primarily compensates too much fine material. The grain size distribution curve for the aggregate should fall within the envelope defined in Figure 6.

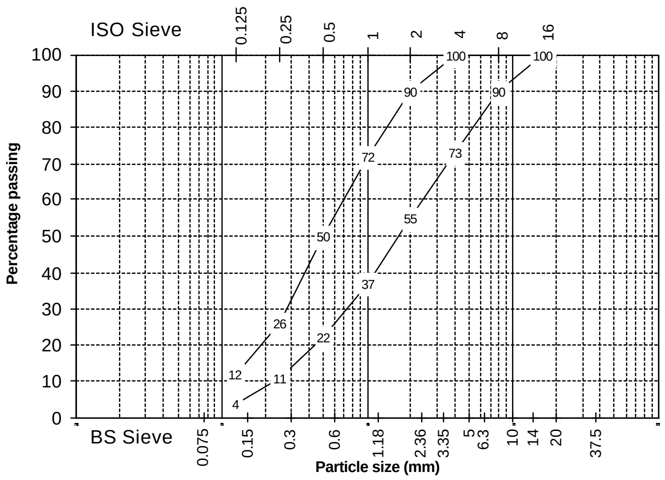


Figure 6: Proposed aggregate grading envelope for sprayed concrete (EFNARC 1996)

The quantity of 8mm 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.

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, comparison tests should be done to establish whether the addition of crushed material gives an improved result.

More recently on major tunnel projects, the environmental need to recycle excavated rock into the aggregates for sprayed concrete has put higher demands on the admixture technology. As experience on the Neat Tunnel, Switzerland, the recycled aggregates are less than ideal, with non-rounded particle geometry or schistose nature giving the mix high internal friction and high water demand. However, the use of microsilica, hyperplasticisers and pumping aid admixtures has provided a workable solution.

3.4 *Admixtures (superplasticisers)*

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 not 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 moldable. The effect must be good, since their structures 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 concrete quality and production have encouraged development, research and use 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 and durability. 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 naphthalene and melamine are often used. This is to obtain the best possible and production-friendly concrete. Naphthalenes/melamines (superplasticisers) are chemically distinct from ligno-sulphonates (plasticisers/water reducers) which are not used for sprayed concrete applications. 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. The effect of superplasticisers to disperse "fines" makes them perfect and needed admixtures for sprayed concrete. The slump increase achieved by adding conventional superplasticisers is time and temperature dependent. However, pumpability can only be maintained for a limited time (20 to 90 minutes) after mixing, and excessive dosages of admixtures can result in a total loss of cohesiveness and in segregation. Normal dosage is from 4 to 10 kg/m^3 depending on the quality requirements, w/c ratio, required consistency, as well as cement and aggregate type.

3.4.1 *Hyperplasticisers - A new generation of special superplasticisers*

A new generation of high performance superplasticisers has entered the market during the last two years. They are based on modified polycarboxylic ether and offer a much higher water reduction than traditional superplasticisers whilst maintaining workability at lower dose rates. These products are referred to as "Hyperplasticisers".

Glenium™ (polycarboxylic) hyperplasticiser: > 40% water reduction

BNS/melamine superplasticisers: 30% water reduction

This opens up new possibilities for sprayed concrete. With these types of admixtures you can produce sprayed concrete with a w/c ratio of 0.38 and with a slump of 15 - 20 cm. The lowering of the w/c ratio enables the following benefits:

- Greatly increased durability
- Longer / better slump retention
- Faster setting
- Higher early strength
- Higher final strength
- Reduced rebound
- Possibility to handle water ingress or to lower the dosage of accelerators (2 - 3 %)

Glenium™ is already being used widely in Europe in combination with alkali-free accelerators. The lowering of water - cement & binder ratios (w/c+b) through admixture technology is given in Figure 7. This is the future generation of sprayed concrete admixtures.

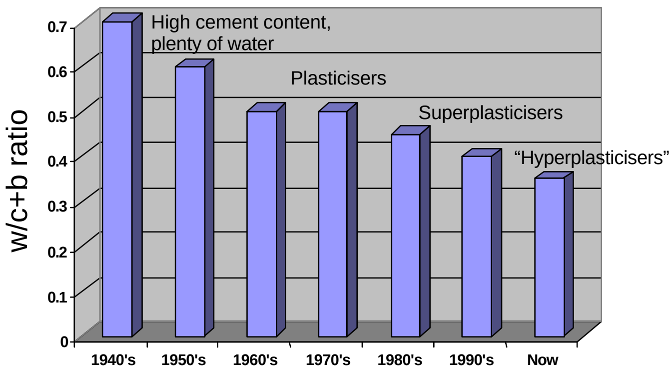


Figure 7: Development of lower w/c+b ratios through admixture technology

3.5 *Hydration control system*

Perhaps one technology that has made the wet-mix so successful in recent years has been the use of hydration control admixtures, such as MBT's Delvocrete Stabiliser.

Before hydration control admixtures were introduced, the wet-mix sprayed concrete system had no flexibility, in that batched concrete had to be used with 1 to 2 hours (and even in less in ambient temperatures in excess of 20°C), otherwise it was discarded as the hydration process made the material unusable. This is indicated as "Traditional sprayed concrete" in Figure 8. This caused several cost and programme problems:

- The supply and utilization of sprayed concrete mixes for infrastructure projects in congested environments created problems for both the contractor and ready-mixed concrete supplier
- Long trucking distances from the batching plant to the site, delays in construction sequences as well as plant and equipment breakdowns ensured that much of the concrete actually sprayed was beyond its ‘pot-life’
- In addition to this, environmental regulations imposed restrictions upon the working hours of batching plants in urban areas, meaning that a contractor who required sprayed concrete mixes to be supplied 24 hours per day, was only able to obtain material for 12 hours a day

To solve these logistical problems, MBT introduced the Delvocrete Hydration Control system in the mid 1990’s. The system comprises two liquid components. The first component is the Delvocrete Stabiliser admixture that is added to the mix at the batching plant. This admixture coats the cement grains and prevents hydration from occurring. Depending on dose, the Stabiliser can provide a hydration controlled mix from 3 to 72 hours, as indicate in Figure 8. However with most sites, a stabilised period of 6 to 8 hours is normally sufficient for most sprayed concrete operations.

The second component to be added at the nozzle with the air is the Delvocrete Activator that immediately disperses the Delvocrete Stabiliser from the cement grains and immediately activates the hydration process. It ensures that all sprayed concrete which is sprayed through the nozzle contains a ‘fresh’ cement that has undergone little or no hydration reactions allowing maximum setting characteristics and early strength development.

The system brings revolutionary benefits to sprayed concrete and is currently being used on a

Traditional sprayed concrete

New flexibility with hydration control

Figure 8: Hydration control for total flexibility in sprayed concrete

significant number of major projects in Europe, America, the Middle East and Far East. By means of example, the currently under construction 3.5km North Downs Tunnel which forms part of the new Channel Tunnel rail Link in the UK, used the following mix design for the permanent sprayed concrete tunnel lining:

- 360kg Rapid hardening cement 52.5N
- 90kg PFA
- 1730kg aggregates (60:40 - sand:crushed granite aggregates)
- 2.5kg Glenium 51
- 4.5kg Delvocrete Stabiliser
- 7% Meyco SA-160 alkali-free accelerator
- w/c+b ratio = 0.38
- Slump: target 200mm

This mix design provided a stabilised mix for up to 6 hours, and the Meyco SA-160 alkali-free accelerator was used as the activator. Figure 9 represents data supplied by the contractor demonstrates the reduction in the number of concrete trucks returned with the introduction of Delvocrete Stabiliser hydration control in May 1999.

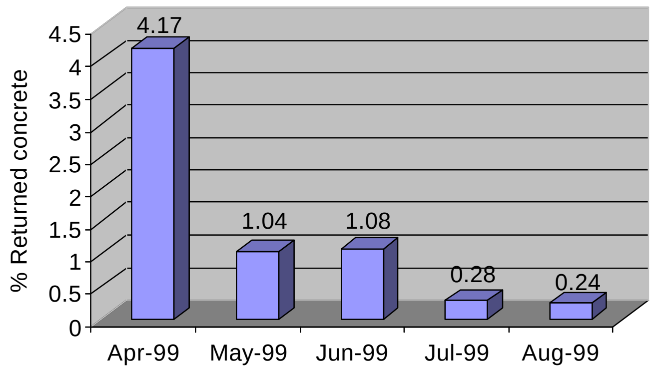


Figure 9: Reduction in returned concrete from site with use of hydration control system

3.6 *Set accelerators*

The wet-mix method needs the addition of fast setting admixtures at the nozzle. The primary effect of the material is to reduce the slump (consistency) at the moment of spraying from liquid to earth moist while the concrete is still in the open air, so that it will adhere to the surface when the layer thickness is increased. This slump reduction must take place in the course of seconds.

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

Accelerators are added in liquid form via a pressure tank or a special dosage pump (piston or worm pumps). The dosage of accelerator will vary, depending on the ability of the operator, the surface and the w/c ratio (high w/c ratios will increase the need for accelerators in order to reduce consistency).

Every coin has two sides. A side effect of the accelerators is the decrease of final strength. Compared to plain concrete (without accelerators), the 28-day strength can be reduced significantly. Therefore, the accelerator consumption should be kept at a minimum at all times (lower consumption on walls than in the roof).

Different types of accelerators are used in sprayed concrete:

- waterglass
- modified sodium silicate
- consistency activators (MEYCO® TCC)
- aluminates (sodium or potassium or a mix)
- alkali-free

Water glass should normally not be used because high dosages (>10 - 12%, normally 20%) are needed consequently significantly decreasing strengths and producing a low quality concrete and a false security. Normal water glass is more or less banned in Europe.

Accelerators containing aluminates should not be used because of their strong negative influence on working conditions and environment. Due to their high pH > 13 they are very aggressive to skin and eyes causing severe burns. Additionally, these accelerators have a pronounced negative effect on the final strength and durability of the sprayed concrete.

3.6.1 *Modified sodium silicates*

Modified sodium silicates give only momentarily a gluing effect (less than 10 seconds) of the sprayed concrete mix (loss of slump) and take no part in the hydration process unlike alkali-free based accelerators. Modified sodium silicates bind the water in the mix and subsequently, dosage is dependent on the w/c ratio: The higher the w/c ratio the more modified sodium silicate is required in order to glue the water in the concrete mix.

Modified sodium silicates do not give very high strength within the first 2 to 4 hours and are therefore not the ideal accelerator for soft ground tunnelling applications, where high early strength is required. Normal final setting occurs after 30minutes, (depending on cement type and ambient temperature).

Advantages of modified silicates:

- Work with all types of cement
- Less decrease in final strengths than with aluminate based accelerators at normal dosages (4 to 6%)
- Very good gluing effect
- Environmentally friendly, not so aggressive for skin. The pH is less than 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 (Na_2O < 8.5%)

Disadvantages of modified silicates:

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

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

In most applications with a reasonable modified 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.

3.6.2 *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 addition, requirements for strength and durability of concrete structures are increasing. Strength loss or leaching effects suspected to be caused by strong alkaline accelerators (aluminates) has forced our industry to provide answers and to develop products with better performances.

Due to their complex chemistry, alkali-free accelerators are legitimately much 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.

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. The typical pH of alkali-free accelerators is between 2.5 and 4 (skin is pH5.5).

3 Environmental protection by reducing the amount of aggressive leachates to the ground water, from both the in-situ sprayed concrete and rebound material deposited as landfill.

4 Reduced difference between the base mix and sprayed concrete final strength compared to older style aluminate and waterglass accelerators that typically varied between 15 and 50%.

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 load bearing), points 2 and 3 are the most important. When sprayed concrete is used for permanent structures, items 1 and 4 become equally important.

As a result of the above demands, in excess of 25,000 tonnes of alkali-free accelerator has been used worldwide since 1995. From MBT's perspective, this accelerator type is considered state-of-the-art, and as a result is currently producing it in 18 countries.

3.6.3 *A family of alkali-free accelerators*

A significant R&D input into alkali-free accelerators has produced a family of products that are suited to most conditions, with performance of the old aggressive accelerators. Today alkali-free accelerators are successful as they perform both with the variation of cement quality and reactivity found around the world, but also meet the demanding sprayed concrete performance required to stabilise poor ground or running water, whilst maintaining good strengths and durability properties.

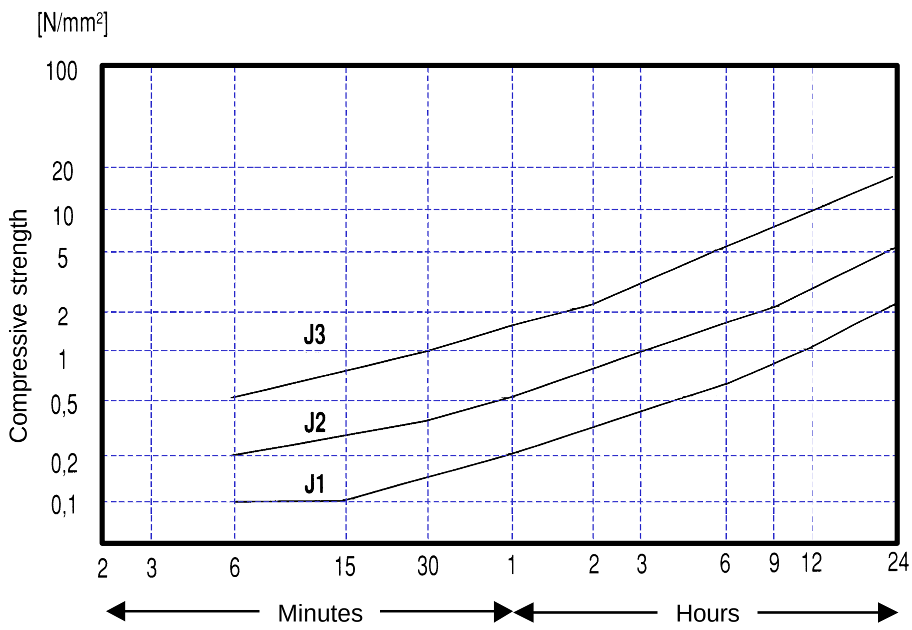
The most widely accepted sprayed concrete early age strength development specification is given in Figure 10 (Austrian Sprayed Concrete Guideline, 1999), where three classes are defined, J_1, J_2 and J_3. For most applications, achieving J_2 is sufficient to achieve good build rates with an early strength development to stabilise tunnel excavations. The final strengths and durability of alkali-free accelerated sprayed concrete in this class will be excellent.

Should the ground be very poor, such as with alluvial deposits and with ground water flow, then J_3 class will be required. High performance alkali-free accelerators, such as Meyco SA-170 are available for these conditions, with very high early strength and moderate long-term strength, as demonstrated in Figure 11. Care must be taken to evaluate the long term durability of sprayed concrete in J_3 class, as often the sprayed concrete is not always compacted sufficiently, and may be cement rich due to high rebound rates.

3.6.4 *Setting and early age strength development – vital considerations*

Confusion exists between sprayed concrete setting and early age strength development. In relation to Figure 10, setting of the sprayed concrete should be considered from 0 to 0.5MPa, this may occur between 6 minutes and 1 hour depending on the dose and type of alkali-free accelerator used, and is measured with a Proctor penetrometer.

Early age strength development should be considered as measurements being above 0.5Mpa and those recorded up to 24 hours age. It is common



Sprayed Concrete Class	Application
J_1	Sprayed concrete suitable for the placing of thin layers on a dry base without special load bearing requirements to be met during the first hours after placing; it offers the advantages of low dust formation and rebound.
J_2	Sprayed concrete that is required to be placed as quickly as possible in thick layers (including overhead). Additionally, sprayed concrete can be applied to water bearing ground, and sections of lining that are immediately adjacent to construction operations involving immediate stress and strain changes, such as new excavations or spiling. In normal tunnel conditions J_2 should not be exceeded.
J_3	Sprayed concrete for support to highly friable rock or excessive ingress of water. Due to the high level of dust and rebound, this class should only be used in limited areas.

Figure 10: Early age sprayed concrete development (Austrian Sprayed Concrete Guidelines, 1999)

Figure 11: Meyco SA-170 alkali-free accelerated sprayed concrete to control active ground water, Blisadonna Tunnel, Austria, 2000

practice to measure these strengths using the HILTI pull-out test method.

Particularly in tunnelling where the sprayed concrete lining will experience the greatest loading directly behind the excavation face (refer to Figure 16), it is crucial that the strength development is continuous after the initial setting, and not remaining dormant until 6 to 10 hours age. In other words, traditional views of a "good" sprayed concrete purely based on fast setting characteristics is dangerous, as limited or no strength development afterwards may endanger the operatives at the tunnel face.

It is vital in soft ground tunnels that the choice of alkali-free accelerators for sprayed concrete should be based on providing setting and strength development characteristics that remain in the J2 and J3 class defined in Figure 10, particularly from 2 to 6 hours age.

3.6.5 *Wet-mix and alkali-free accelerators enable economical permanent sprayed concrete structures*

Wet-mix sprayed concrete coupled with the new alkali-free accelerators has equipped the sprayed concrete industry with a method of placing high performance concrete.

Of particular benefit is the tunnelling industry that traditionally constructed tunnels with two shells: The first shell being temporary sprayed concrete that was not of sufficient quality to contribute to the long term design requirements. This was then followed by a permanent cast in-situ concrete shell on the inside.

With the use of alkali-free accelerators and the wet-mix process, primary tunnel linings can be considered as permanent support elements. As a permanent element of the structure, a lighter second lining may be required to improve watertightness and aesthetics, acting monolithically with the first layer to form a single shell. Where watertightness and finish are not critical, a single layer may be adequate (see Figure 12).

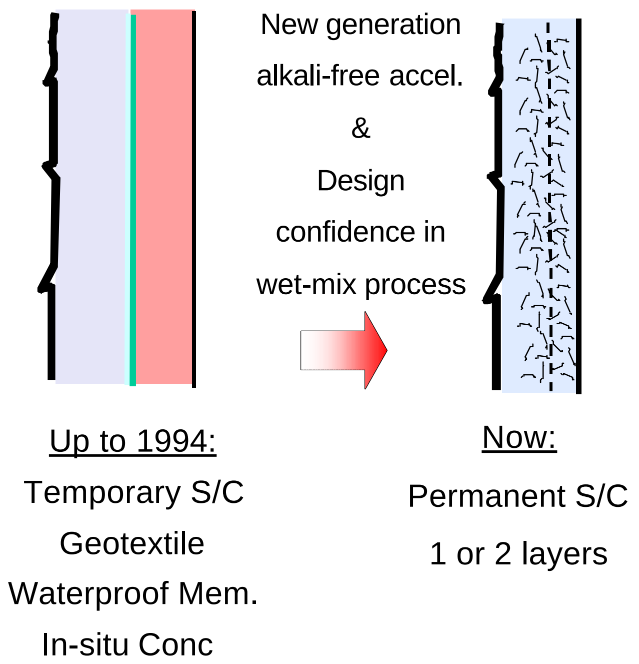


Figure 12: Wet-mix and alkali-free accelerators permit single shell linings for tunnels

By means of example, the North Downs Tunnel, UK, opted to use the primary sprayed concrete lining of the tunnel as a permanent structural element. This allowed the following savings to be achieved:

- Reduced excavation size
- Reduced overall lining thickness
- Reinforcement of second in-situ concrete layer removed
- Reduced landfill requirement
- Reduced programme

By using alkali-free accelerator Meyco SA-160 and the wet-mix process, the material and programme benefits allowed a cost saving of £10M for a tendered £80M project (13% saving). With this in mind the tunnelling industry appears to have adopted

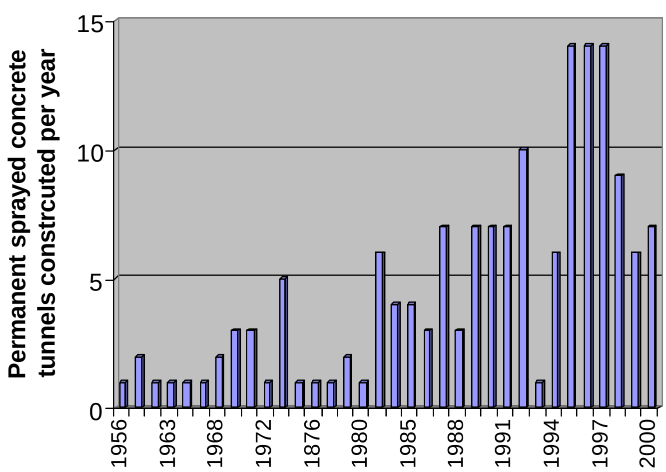


Figure 13: Number of permanent sprayed concrete tunnels constructed per year worldwide (source: ITA-AITES, 2000)

sprayed concrete as a permanent lining material demonstrated by the ever increasing number shown in Figure 13, particularly with the introduction of alkali-free accelerators in 1996. (The apparent recent decrease is due to not all current data being provided to the ITA-AITES database).

3.7 *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.

3.7.1 *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 consequential high shrinkage and cracking potential of the applied concrete. Other reasons are the danger of rapid drying out due to the heavy ventilation as is usual in tunnels, and 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 confined spaces), 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 become significant. These requirements are good bonding, high final density and compressive strengths to ensure freeze/thaw and chemical resistance, 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 worldwide, 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. 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. As a consequence the curing process is poorly achieved, if at all.

3.7.2 *Concrete improving*

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 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 onset of hydration
- There is no negative influence on bonding between layers enabling structures to act monolithically without the risk of de-lamination
- Acts on the whole thickness of the concrete lining, rather than just the exposed surface

Figure 14 illustrates typical bond strength results for sprayed concrete samples that have no curing, a spray applied curing membrane and finally, a sprayed concrete containing Meyco TCC735 Concrete Improving admixture. The externally cured sprayed concrete gives the worst performance as the membrane has had a negative influence on the bond strength. The effectiveness of the Concrete Improver is also seen with age, as demonstrated by the increase between 10 and 28days.

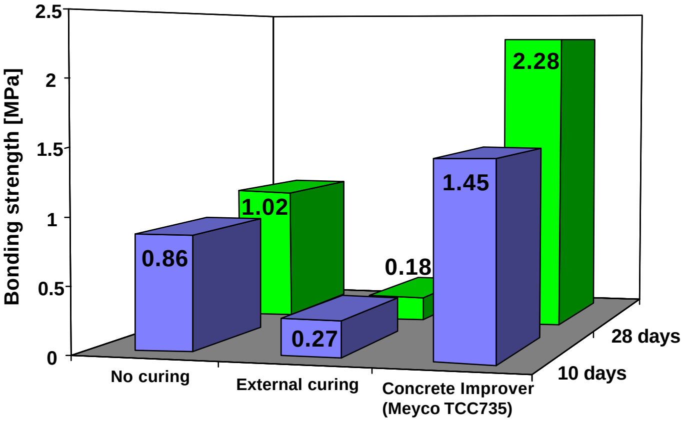


Figure 14: Positive influence of using Concrete Improvers to enable increased bond strength (e.g. Meyco TCC735)

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

4 NEW FIBRE REINFORCED SPRAYED CONCRETE TECHNOLOGY

The advantages of fibre reinforcement in sprayed concrete have been demonstrated in numerous projects and applications around the world. When using state of the art technology, the technical performance of fibre reinforcement is generally equally good or better than traditional mesh reinforcement. Additionally, it is giving a number of other advantages:

- Overall productivity when applying on drill and blast rock surfaces is often more than doubled
- Substantially improved safety, while sprayed concrete and reinforcement can be placed by remote controlled manipulator (nobody venturing below partly supported or unsupported ground to install the mesh)
- No areas of poor compaction behind overlap areas of 3 to 4 layers of mesh, causing very poor concrete quality and high risk of subsequent mesh corrosion and concrete cover spalling
- The intended thickness and overall quantity of sprayed concrete can be achieved quite accurately and the problem of excess quantity to cover the mesh on rough substrates is avoided
- One layer of mesh will be placed at varying depth in the sprayed concrete layer and cannot be placed in the cross section to target tension zones. The fibres will be present in the whole cross section, irrespective of where the tension will occur
- Logistic advantage of avoiding handling and storage of reinforcement mesh under ground

To be able to achieve the above advantages the wet-mix application method has to be used. The reason for this is the lack of control and the large amount of fibre rebound in the dry process. Typically the steel fibre rebound in the dry process is above 50% and using synthetic fibres it is likely to be even higher. In comparison, steel fibre rebound is typically 10 to 15% in the wet mix process.

Until now, the steel fibres have been the only alternative to mesh reinforcement. Lately the High Performance Polypropylene (HPP) fibres have reached a performance level that is comparable to steel fibres, and are set to be a viable alternative in the future.

4.1 *High Performance Polypropylene Fibres (HPP)*

Recently, developments in the US (Synthetic Industries) have come up with a new type of plastic fibre that resembles more a steel fibre in terms of shape and form. The so called new HPP plastic fibres are made of high quality materials and are delivered in a length of 35 and 50mm with a geometry specifically designed to resist matrix pull-out (see Figure 15), enhancing the concrete performance even after it has developed stress cracks. Different test results from Australia and Europe show that this type of fibre can reach a suitable toughness if dosed moderately (10 - 13 kg/m^3). The tests show that these 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 kg/m^3 of high quality fibres.

Additional benefits of the HPP fibre over steel fi-

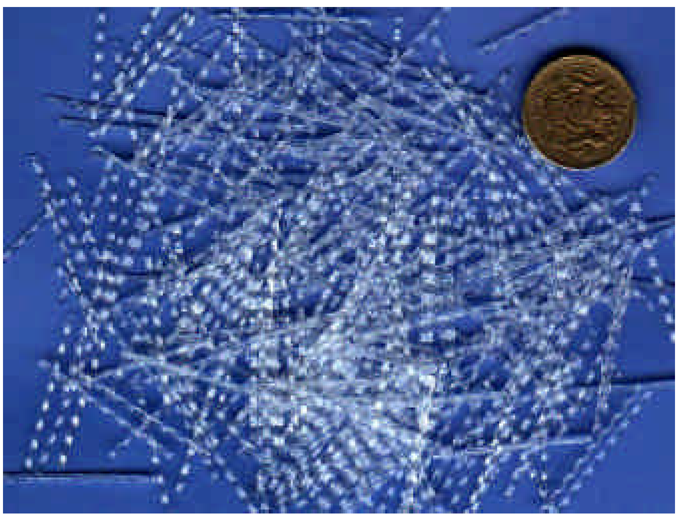


Figure 15: High Performance Polypropylene fibres (HPP) for sprayed concrete

bres are listed below:

- Properly designed high volume synthetic fibres are typically more user friendly in pumping, spraying and finishing compared to steel fibres
- HPP fibres result in lower pump pressures and less wear and tear on the pumping equipment, hoses and nozzles than steel fibres.
- Where finished surfaces are required, the HPP reinforced sprayed concretes typically are easier to cut, trim and finish than steel fibre reinforced sprayed concretes.
- High volume HPP reinforced sprayed concrete typically display better residual load carrying capacity at larger deformations compared to steel fibre reinforcement. This is particularly beneficial in squeezing ground and mining activities where rock bursts are likely.
- The performance of steel fibres is based on their ability to bridge cracks. If exposed they can corrode thereby reducing their reinforcing role. Clearly, HPP fibres, being synthetic can bridge cracks without a corrosion risk.
- Concrete structures in severe chemical exposure environments, such as sub-sea and coastal tunnels, will benefit from a non-corrosive fibre such as HPP.
- Protruding HPP fibres do not cause skin lacerations, as is often considered a negative aspect to exposed steel fibres.

4.2 *Future insight into fibre reinforced sprayed concrete for permanent structures*

Figure 16 simplifies the current knowledge levels concerning fibre reinforced sprayed concrete tunnel linings as a permanent structural element. As the tunnel environment is probably the most demanding on sprayed concrete performance both during construction and throughout the operational life of the structure, the knowledge gained can be used in most other ground and civil engineering applications.

The following list suggests areas of study into fibre reinforced sprayed concrete that should receive attention of the next five years so that a more complete understanding of the material performance is acquired:

- As fibre reinforced sprayed concrete was introduced in large projects during the mid 1970s, the long-term durability assessment has only been based on in-situ tunnel samples, particularly in Norway, up to an age of 25 years. Early indications from these studies have demonstrated the sprayed concrete to be in good condition, with compressive strengths similar to those achieved at 28days. Fibres have been shown to corrode near exposed surfaces, but show little signs of corrosion within the main section of the linings. Considering these sprayed concrete mixes had w/c ratios in excess of 0.45, the durability of more recent sprayed concrete linings will be further improved. However, studies on the long-

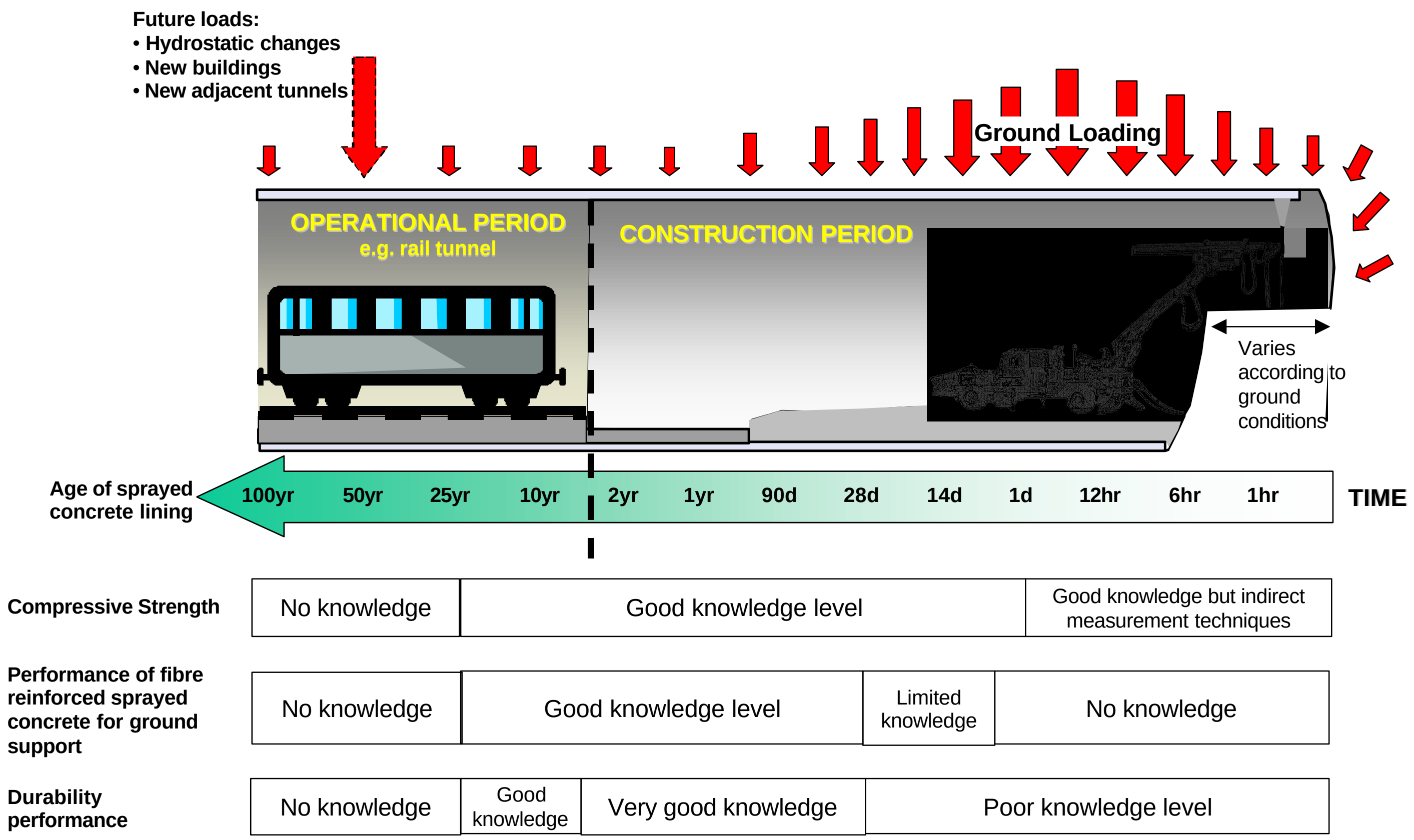


Figure 16: Short to long-term knowledge base for fibre reinforced sprayed concrete tunnel linings

term durability of existing sprayed concrete linings needs to be continued so that an understanding of structural decay and whole life costing models can be established.

- From Figure 16 it can be noted that significant loads onto the tunnel lining are normally within a tunnel diameter of the face excavation. In modern day tunnelling, this represents sprayed concrete of less than 1 day in age. It is acknowledged that the young age sprayed concrete lining behaves plastically at this stage, allowing a redistribution of stresses throughout the lining, thereby reducing adverse moments. However, the role achieved by fibre reinforcement during these vital early ages has not been evaluated to a large extent. When referring to durability of sprayed concrete linings, it is this early stage that may define the future performance of the lining, and it is conceivable that fibre reinforcement has a significant benefit in this regard.
- Significant amounts of testing and reporting on post failure performance of fibre reinforced sprayed concrete is available today. This is extremely beneficial to the hard rock tunnelling and mining market, where rock support relies on this material performance for both short-term construction safety, and long-term operational security. In respect to soft ground tunnels, this information is of minimal value apart from during the safety benefits during construction. The soft ground tunnelling industry requires further insight into the benefits of fibre-reinforced sprayed concrete, for example in terms of achievable flexural strengths relating to fibre type, and to the benefits and design recommendations to achieve durable, anti-crack sprayed concrete linings. Currently, only small-scale tests on concrete rings using unknown steel fibre types have guided the industry to a dose of $40kg/m^3$ of steel fibre to maintain crack widths to 0.2mm. More recent studies have shown relationships between fibre diameter and length to calculate fibre dosages for anti-crack reinforcement, but no actual tests have been achieved to the authors' knowledge.

5 SPRAYED CONCRETE EQUIPMENT

The application of sprayed concrete via poor equipment may ruin all the efforts made by composing a good concrete mix design and other actions taken to produce a high quality concrete. Only with a balanced system of reliable spray 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 constant innovative development in the equipment sector to produce machines suited for the new products and that are adaptable to the ever-changing conditions in the construction business. The result is a wide range of systems that cover all sprayed concrete works: from major tunnelling contracts 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 that ensure higher production output, consistent and controllable quality, as well as safer and more operator-friendly working conditions.

Development of the dry-mix equipment is considered to be at its limit, and in view of the international trend towards wet-mix application methods, the development is almost entirely via wet-mix sprayed concrete equipment.

5.1 *Developments*

To ensure even spraying, the latest equipment developments aim at providing a pulsation-free conveyance of the wet-mix from the pump to the nozzle.

This is put into practice with the MEYCO® Suprema: The electronically controlled push-over system that is integrated into the output adjustment brings the pulsation of the material flow to a minimum that 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 synchronises the dosing of accelerator to the concrete output of the pump. This is of critical importance when constructing permanent sprayed concrete structures so as to reduce the risk of reduced strength and durability with overdosing.

5.2 *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 mechanised 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)

5.3 *Spraying mobiles*

Many suppliers also offer complete mobile systems with integrated equipment for the complete spraying job, as shown in Figure 17.

Figure 17: Meyco Spraymobile – complete sprayed concrete system on board vehicle

A Spraying Mobile typically consists of:

- Wet-mix spraying machine/pump
- Spraying manipulator
- Accelerator storage tank
- Dosing unit for accelerator
- Cable-reel with hydraulic drive
- Air compressor, capacity 12 m^3/min
- Central connection and control system for external power
- High pressure water cleaner with water tank
- Working lights

The benefits of echanised spraying can be summarised in the following:

- 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.

Essential to some specialist sprayed concrete contractors is the flexibility to take a spraymobile onto the road network and be able to travel between sprayed concrete project sites, without the need for unnecessary site set-up time associated with individual compressors and generators etc. To address this need the Meyco Roadrunner (Figure 18) was developed, and has found a strong market in Scandinavia.

Figure 18: Meyco Roadrunner - road worthy spraymobile

For the mining market, a small version spraymobile is required, such as the Meyco Cobra. Due to the severity of the mine roadways and drifts, this type of rig must have a robust, articulated chassis. Again all equipment for spraying wet-mix sprayed concrete is included on the rig. An example of this type of machine is given in Figure 19

Figure 19: Meyco Cobra - Mining industry spraymobile

5.4 *State of the art the latest generation of concrete spraying robots*

Spraying manipulators or robots are suitable for use wherever large quantities of sprayed concrete are applied. A new machine, Meyco Logica based on the worldwide well known kinematic principle of the MEYCO® Robojet has now been developed. In cooperation with Industry and University for this manipulator with 8 degrees of freedom a new automatic and human oriented control system has been developed. The new tool 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 (See Figure 20). The calculation of the kinematics is done by the control system. A laser scanner sensor measures the tunnel

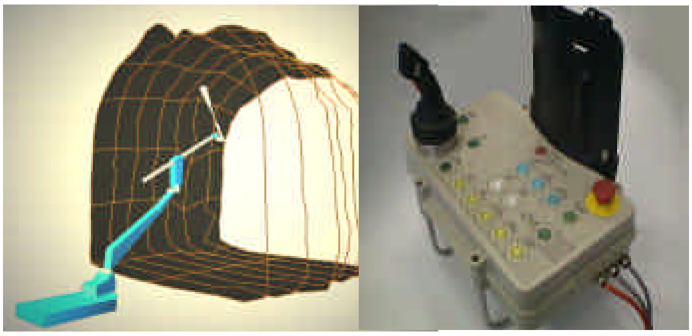


Figure 20: Meyco Logica - fully automatic spraymobile system

geometry and this information is used to control automatically the distance and the angle of the spraying jet.

The aim of this control 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. With the correct angle and continuously constant spraying distance a remarkable reduction in rebound and therefore savings in cost are achieved. Furthermore, if the tunnel profile is measured after spraying, too, the system will give information of the thickness of the applied sprayed concrete layer which was up to today only possible with core drilling and measurement. If an exact final shape of a tunnel profile is required, the control system manages the robot to spray to these defined limits automatically.

5.5 *Nozzle systems*

Nozzle systems are an important part of the spraying equipment. Through proper mixing of accelerators and air in the wet-mix spraying method, nozzles can significantly contribute to:

- Lowering rebound
- Improving bond strengths
- Improving compaction
- Reducing dust levels

Only with the correct nozzle system - 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. A typical wet-mix nozzle system is shown in Figure 21.

6 NEW DEVELOPMENTS

This section highlights some of the improvements that have been made relating to the sprayed concrete industry, other than those that have been reviewed in the previous sections.

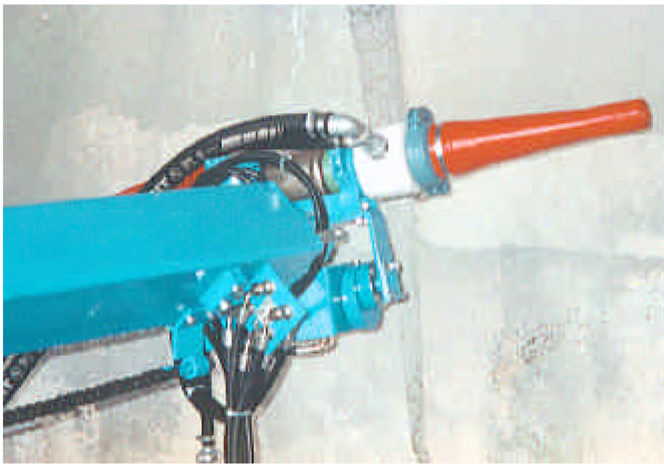


Figure 21: Meyco wet-mix nozzle system

6.1 *Achieving watertightness – sprayable membranes*

With the advent of single shell permanent sprayed concrete linings, there has also been a request by the industry to provide watertight sprayed concrete. This is of particular importance with public access tunnels and highway tunnels that are exposed to freezing conditions during winter months, and also electrified rail tunnels. It has been shown that most permanent sprayed concrete exhibits an extremely low permeability (typically 1 x 10^{-14}m/s), however water ingress tends to still occur at construction joints, at locations of embedded steel and rockbolts.

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:

1 As the sheet membranes are point fixed, sprayed inner linings may not to be in intimate contact via the membrane to the substrate. This may lead to asymmetrical loading of the tunnel lining.
2 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.
3 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. This is a detrimental effect when constructing monolithic structures.
4 As there is little bond strength at the concrete - sheet membrane interface, any ground water will migrate in an unlimited manner. Should the membrane be breached, the ground water will in-

evitably seep into the inside tunnel surface at any lining construction joint or crack over a considerable length of tunnel lining.

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 thereby effectively preventing any potential ground water paths on both membrane–concrete interfaces being created. Masterseal® 340F also has an elasticity of 80 to 140% over a wide range of temperatures allowing it to bridge any cracks that may occur in the concrete structure. Being a water based dispersion with no hasardous components, it is safe to handle and apply in confined spaces. The product can be sprayed using a screw pump and requires two operatives to apply up to 50m²/hr, particularly in the most complex of tunnel geometries, where sheet membranes have always demonstrated their limitation, as shown in Figure 22.

As presented in Figure 23, in single shell lining applications, Masterseal® 340F is applied after the first layer of permanent fibre-reinforced sprayed concrete, where the sprayed surface should be as regular as possible to allow an economical application of membrane 5 to 8mm thick (all fibres are covered also). 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 1MPa, the structure can act monolithically, with the sprayable membrane resisting up to 15bar. 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.

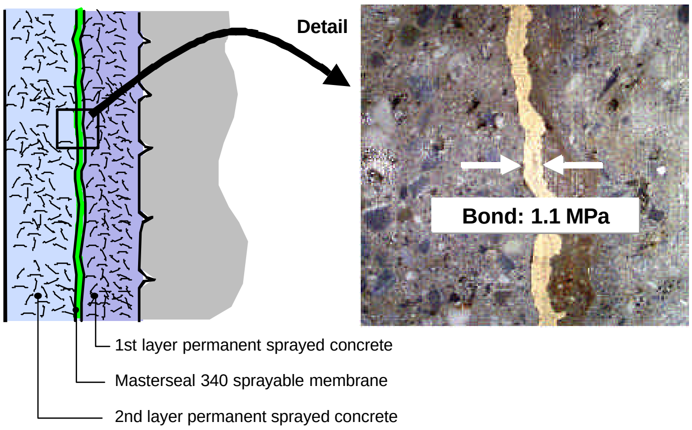


Figure 23: Composite, watertight structures using Masterseal 340F sprayable membrane

Figure 22: Using a simple screw pump, two men can apply sprayable membrane up to 50m² per hour

6.2 *Modern admixtures provided necessary properties for wet-mix sprayed concrete delivery to deep shaft construction*

The Sedrun Access Shaft constitutes one of three intermediate adits along the 57km Gotthard Base Tunnel, part of the New Alpine Rail Transit system in Switzerland. Because of the elevation of the terrain along the tunnel, the Sedrun intermediate adit is being constructed as an 800m deep vertical shaft with a diameter of 9 m.

Having readily available concrete at the bottom of a shaft during sinking involves several challenges within concrete technology and concrete logistics. Transport by means of a vertical free flow through a pipeline requires special mix design considerations, as well as special technical solutions regarding the actual transportation line.

Typical problems are blocking of the pipeline due to bridging inside the pipe and segregation of the mix, causing the coarser fragments of the aggregate to travel faster than the fines. This in turn causes blockages consisting of gravel. Critical fresh concrete properties to prevent these problems are high slump retention to avoid bridging and a high level of cohesiveness to avoid segregation and bleeding.

To overcome these difficulties, the desired combination of the fresh concrete properties of high slump retention and high cohesiveness led to the following main mix design features:

- High binder content
- Hyperplasticiser with extremely high water reducing effect
- Special aids for increased cohesiveness

As a special aid for increased cohesiveness, the product MEYCO® TCC780 is used. This product gives particularly good contribution to cohesiveness and pumpability with difficult and uneven gradation conditions in the aggregate.

The bottom of the pipeline was equipped with a kettle for remixing and removal of kinetic energy, allowing concrete to flow gently into a kibble for buffer storage and subsequent spraying.

6.3 *Surface finish*

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

Sprayed concrete can be surface finished by screeding and hand floating to produce a surface finish similar in quality to that of a cast in-situ concrete. This process is performed to a sprayed mortar layer applied to the final structural sprayed concrete layer, and is typically 25mm thick. Polypropylene fibres may be included in the mix design to control surface crazing produced by thermal and surface drying effects. In tunnels, the screeding process is relatively simple to perform using 25mm diameter screed profiles bent to the finished profile of the tunnel, and if required, further improvement to the surface finish can be attained by hand float work, as illustrated in Figure 24. Purpose made power floats are also available to aid this task. As these finishing layers tend to be relatively thin coats, concrete improving admixtures should be used to aid bond strengths and efficiently cure the concrete.

Following recent tunnel fires where considerable structural damage resulted, the use of 50mm thick spray applied cementitious based, fire protective layers can be applied. These coatings provide fire protection up to1350^{o}C, and can be float or screed finished as described above.

If a high reflectance and colour is required, the application of a pigmented cementitious fairing coat or a coloured epoxy coating to the may be used.

Figure 24: Screed and float finish permanent sprayed concrete tunnel

6.4 *Electronic penetrometers*

As discussed earlier, the selection of the sprayed concrete system is based on the setting characteristics and early age strength gain, determined essentially by cement-accelerator reactivity and low w/c ratios. In the laboratory, the setting characteristics are examined using the Vicat test, but during development of the mix during site trials, the testing has been achieved using a Proctor penetrometer, as indicated in Figure 25.

Figure 25: Traditional Proctor penetrometer where full body weight required (Jubilee Line Project, UK, 1994)

There are numerous influences on the recorded result using this equipment, such as:

- Penetrometer needle hits large aggregate rather than sandy matrix, giving higher results
- Angle of penetration not always perpendicular to sprayed concrete surface
- Penetration often exceeds the required 15mm depth due to the excessive force applied to the penetrometer (see Figure 25, where full body weight needs to be applied!)
- Use and results dependent on operator to high degree

To combat these negative influences, the use of an electronic penetrometer as illustrated in Figure 26, providing the following benefits:

- Shorter and pocket sized instrument making it easier to handle and reduce errors

- More accurate, faster measurements producing data with significantly less variance than traditional penetrometers
- Guidance ring on needle to help with correct penetration depth
- Calibration of instrument is simple
- All results can be downloaded to a PC
- Can also be used as a 50kg balance which is useful during site trials

Figure 26: Pocket-sized electronic penetrometer for measuring setting and early age strength development

7 RAISING COMPETENCE

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 that 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 implemented.

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.

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.

Likewise, the construction team should be made aware of the design elements that are key factors in determining the safety and durability of the 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.

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 certification, 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, are providing courses in modern sprayed concrete technology to address the shortcomings in the industry. Specific courses are available for designers and contractors, with specialist nozzleman training for robotic spraying for example.

8 OTHER APPLICATIONS

The emphasis of this paper has been on sprayed concrete for tunnel and ground support applications as this market uses the highest volume. Nevertheless, the versatility of sprayed concrete through the benefits of free-form design without the need for formwork, high quality concrete, early strength development and high bond strength has proved highly effective as demonstrated by the following examples.

8.1 *White water rafting course, Sydney 2000 Olympic Games, Australia (Figure 27)*

In Sydney, Australia, this white water rafting course was constructed for the 2000 Olympic Games using polypropylene fibre reinforced sprayed concrete. The inside walls were designed to resist turbulent

Figure 27 *(Courtesy: Synthetic Industries)*

water and repeated battering from canoes. This continuous structure, which contains joints, is capable of generating water-flow rates of up to four meters per second along the 300 linear metre course.

8.2 *Oro Valley channel, Arizona, USA (Figure 28)*

In Oro Valley, Arizona, 50mm long polypropylene fibers were used in the sprayed concrete mix design instead of traditional reinforcement for this channel lining due to the concerns about post-crack integrity. The sprayed concrete thickness was 150mm.

Figure 28 *(Courtesy: Synthetic Industries)*

8.3 *Seismic dam retrofit, Little Rock Dam, California, USA (Figure 29)*

2km away from the San Andreas Fault, the Little Rock Dam required a retrofit using a ready mix supplied, air-entrained, steel fibre reinforced, silica fume, wet-mix sprayed concrete.

Critical to the successful implementation of the design was the achievement of a minimum direct bond tensile (pull-off) strength of 1.0 MPa and a crack-free material.

The use of a high performance steel fibre reinforced sprayed concrete and the rigorous implementation of the specified curing regime were considered critical in ensuring successful completion of this project in a severe desert climate.

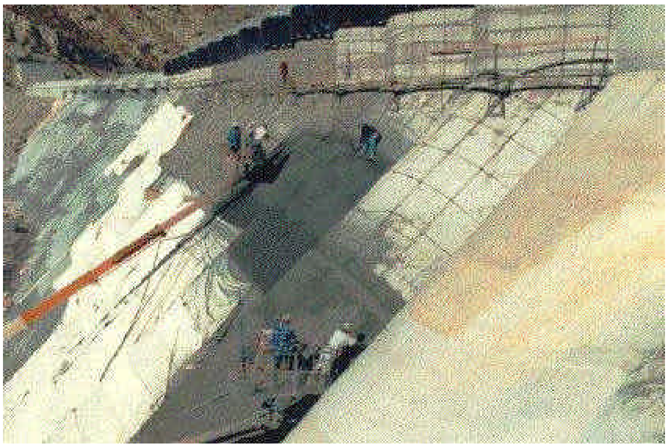


Figure 29 *(Courtesy: DR Morgan, AGRA Earth & Environmental Ltd)*

8.4 *2nd Dover Cruise Liner Pier, UK (Figure 30)*

In view of the aggressive environment, 400 2m diameter steel piles that support the new cruise liner pier and side fenders required additional corrosion protection between low and high tide marks. After reviewing all coating systems, high performance sprayed concrete was selected due to the fast application and strength gain, but also long-term durability.

The sprayed concrete mix contained monofilament polypropylene fibres, a high microsilica content, concrete improver admixture for bond, and was accelerated with alkali-free set accelerators. The concrete was applied during the outgoing tide from a pontoon, so that on the return tide the concrete had acquired adequate strength not to be eroded.

Sprayed concrete for coastal protection works has significant benefits over conventional methods.

Figure 30 *(Courtesy: Spraycon Ltd)*

8.5 *Cement Storage Domes, Ontario, Canada (Figure 31)*

Located in Ontario, Canada a 55m diameter, 29m high dome to store 66,000 tonnes of cement powder was constructed using only high performance sprayed concrete applied to a pre-inflated plastic form. Such structures have found a considerable market in both North and South America, and with one structure being constructed in Germany.

Figure 31 *(Courtesy of Domtec Ltd)*

9 CONCLUSIONS

Wet-mix sprayed concrete applied using modern environmentally safe admixtures and high performance equipment equips the industry with an economical tool to construct permanent, high strength, durable concrete structures. The application 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 structural material.

The development of sprayed concrete has, and continues to be, centred on the wet-mix method and used almost exclusively in the underground support market in significant volumes since the 1970s. The larger international contractors that have had prior knowledge of the benefits have orchestrated the international spread of the wet system. Consequently, wet-mix sprayed concrete has been confined to countries with large-scale tunnel or mining projects. The transfer of technology to the other domestic markets that use the dry-mix method has been slow, but the tendency has been towards wet-mix in the last 10 years. 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 time and cost saving potential in application of wet-mix 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 such permanent support measures. Also, contract terms that are counterproductive for the utilisation of modern support techniques must be avoided.

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. Wet mix sprayed concrete is no longer an experiment, as the solutions are well proven.

Sprayed concrete as a building method would have a much larger applications outside tunnelling, however, presently the use of the system is still extremely under used. One of the advantages of the sprayed concrete is its flexibility and speed. Concrete which is to be applied simply with a hose against formwork, rock surface or concrete surface, may architecturally and constructively be varied. The only limit is imagination and the desire for experimentation.

We therefore call upon all contractors, architects, authorities and consultants that the concrete technology, experience, equipment and materials exist and may be mobilised to increase the range of our building activities as soon as someone plucks up courage to embrace the building method of the future: sprayed concrete.

Developments within sprayed concrete technology are listed in Table 4, with summarised areas of work that are required to further sprayed concrete implementation.

Table 4: Sprayed concrete development and future work

What has been achieved	**Further work left**
Spraymobiles	
• Reliable machines with few breakdowns and low running costs	• Develop accurate concrete flow-meters
• A nearly pulsation free concrete flow to nozzle allowing homogeneous concrete to be placed	• Simplify transfer of recorded data into a laptop
• Sufficient spray capacity, theoretical up to 30m³ (effective 20-25m³), 5 to 8 times that of dry-mix systems	• Enable to spray automatically to a defined contour
• Accelerator dosing linked to concrete pump to not cause strength and durability problems, and to control site costs	• Completely pulsation-free machines with maximum piston efficiency
• Store data recorded during spraying	
• Spray a defined concrete thickness automatically	

What has been achieved	Further work left
Design, Health and Safety	
• Sprayed concrete accepted as permanent in some countries	• Sprayed concrete in many countries still considered temporary
• Specifications for dust have been established	• Concrete strength requirements still at 25 MPa
• Caustic accelerators banned in some countries	• Promote single shell lined tunnels
	• Dust specifications not enforced in most countries
	• Spray operations often done in unsupported areas
	• Caustic accelerators still in use in some countries
	• Mechanised robotic spraying offering increased safety to operatives at face
	• Introduce design and safety advantages to other markets e.g. concrete repair
Construction Chemicals and Fibres	
• New generation of superplasticisers	• Improve superplasticisers to cope with even more difficult aggregates
• Hydration control for up to 72 hours	• Find improved test procedure for accelerator laboratory tests
• Alkali-free accelerators with excellent setting characteristics	• Improve accelerator storage and handling properties
• Accurate weight and volume based batching systems for admixtures and fibres	• Implement systems to facilitate admixture and fibre batching on non-dedicated sprayed concrete plants
	• Fully understand the benefits of fibre reinforcement and implement in designs

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