Shotcrete in Tunnel Construction

Introduction to the basic
technology of sprayed concrete

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Experts on Sprayed Concrete

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Foreword

Sprayed concrete is an excellent tool for stabilisation and support of structures in a very short time and for concrete applications without using any moulds. Sprayed concrete is also the interaction of man, machine and concrete. Sprayed concrete is a high-performance material which functions only as well as these "three components of success". Man, personified in the work of the nozzle man, requires great technical skill and dedication to the job. The operator must be able to rely fully on the machine and the sprayed concrete material. It is the interaction and quality of these components that finally determines the success of the sprayed concrete application.

In times of rapidly increasing mobility and limited space, the need for underground infrastructure continues to grow. Sprayed concrete has an important role in this requirement. This method is economically outstanding and almost unlimited technically, making it the obvious answer.

Against this background, Putzmeister AG and Sika AG have formed a global strategic alliance for sprayed concrete in tunnelling and mining. The alliance ensures that our customers will see innovative, continuous and relevant ongoing development of sprayed concrete machines and admixtures for very high demands in highly-mechanised installation of sprayed concrete.

The best in sprayed concrete technology and machine know-how is now combined.

In this context, the two companies have also decided to publish this booklet to make it easier for interested parties to take the fascinating step into the world of sprayed concrete in underground construction.

Its authors Jürg Schlumpf and Jürgen Höfler have worked in the two companies for many years as engineers in project and product management. This booklet is written both as an introduction to sprayed concrete and its application and for a deeper study of this outstanding construction method; it is intended as a reliable source of information for our partners.

March 2004

Experts on Sprayed Concrete

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2. Introduction

Over the past century, sprayed concrete has replaced the traditional methods of lining tunnel profiles and has become very important in stabilising the excavated tunnel section. Modern tunnelling without sprayed concrete is inconceivable. Sprayed concrete is a single term that describes various components of a complete technology:

- the material sprayed concrete
- the sprayed concreting process
- the sprayed concrete system

These three components define a complete technology which has a long tradition, huge potential for innovation and a great future. The material sprayed concrete is a concrete mix design that is determined by the requirements of the application and the specified parameters. As a rule, this means a reduction in the maximum particle grading to 8 mm or max. 16 mm, an increase in the binder content and the use of special sprayed concrete admixtures to control the properties of the material. Sprayed concrete was used for the first time in 1914 and has been permanently developed and improved over recent decades.

Fig. 1: Sika®-PM500 PC – joint venture for the TRANSCO Los Sedrun Gotthard base tunnel

There are now two different sprayed concrete processes:

- **dry process sprayed concrete**
- **wet process sprayed concrete**

The main mix requirements focus on the workability (pumping, spraying application) and durability; they are:

- high early strength
- the correct set concrete characteristics
- user-friendly workability (long open times)
- good pumpability (dense-flow delivery)
- good sprayability (pliability)
- minimum rebound

The sprayed concreting process designates its installation. After production, the concrete is transported by conventional means to the process equipment. Sprayed concrete or sprayed mortar is fed to the point of use via excess-pressure-resistant sealed tubes or hoses and is sprayed on and compacted. The following methods are available for this stage of the process:

- **the dense-flow process for wet sprayed concrete**
- **the thin-flow process for dry sprayed concrete**
- **the thin-flow process for wet sprayed concrete**

Before being sprayed, the concrete passes through the nozzle at high speed. The jet is formed and the other relevant constituents of the mix are added, such as water for dry sprayed concrete, compressed air for the dense-flow process and setting accelerators when required. The prepared sprayed concrete mix is then projected onto the substrate at high pressure which compacts so powerfully that a fully-compacted concrete structure is formed instantaneously. Depending on the setting acceleration, it can be applied to any elevation, including vertically overhead.

The sprayed concrete process can be used for many different applications. Sprayed concrete and mortar is used for concrete repairs, tunnelling and mining, slope stabilisation and even artistic design of buildings. Sprayed concrete construction has various advantages:

- application to any elevations because sprayed concrete adheres immediately and bears its own weight
- can be applied on uneven substrates

- good adhesion to the substrate
- totally flexible configuration of the layer thickness on site
- reinforced sprayed concrete is also possible (mesh/fibre reinforcement)
- rapid load-bearing skin can be achieved without forms (shuttering) or long waiting times

Sprayed concrete is a flexible, economic and rapid construction method, but it requires a high degree of mechanisation and specialist workers are essential.

Fig. 2:
dry spray application

Fig. 3:
wet spray application

3. Applications of sprayed concrete

Sprayed concrete construction is used in many different types of project. The flexibility and economy of this material comes to the fore in above-ground and underground buildings, tunnelling and special underground construction, in fact throughout the construction industry. The following uses are widespread:

- excavation stabilisation in tunnelling and underground construction
- tunnel and underground chamber lining
- stabilisation in mine and gallery construction
- concrete repair (concrete replacement and strengthening)
- restoration of historic buildings (stone structures)
- sealing works
- trenching stabilisation
- slope stabilisation
- protective lining
- wearing courses
- special lightweight load-bearing structures
- creative applications

In terms of importance, tunnelling, mining and concrete repairs head the list. In tunnelling and mining, the main uses are for excavation stabilisation, temporary and permanent arch lining. Sprayed concrete is also used for all other appropriate concreting works. Large cavities are often spray filled, for instance. Sprayed concrete has confirmed and strengthened its position alongside tunnel segment lining (tubbing) and interior ring concrete as the main concreting method. The limits on its use lie in the technical and economic interfaces with the other concreting processes and/or construction methods.

Fig. 4: Driving sprayed concrete laboratory

3.1 Types of construction

Sprayed concrete is used in all areas of tunnel construction – for road or rail tunnels, water drainage and underground military structures, in addition to slope stabilisation. Whether tunnelling under a building or driving through an obstruction, the construction method is determined by the weight-bearing properties and stability of the substrate tunnelled through. The main distinction is between full excavation of the entire section in one operation and partial excavation in many different forms and methods. If full excavation is not possible due to the rock stability, the final profile is often excavated in several phases.

In underground construction, because high stresses would often be exerted on the newly placed excavation stabilisation and lining. Predetermined deformation of the excavated section is often allowed and only then is the stabilisation given a non-positive seal. This causes the stresses to be distributed around the excavation section and in the area around the excavation face.

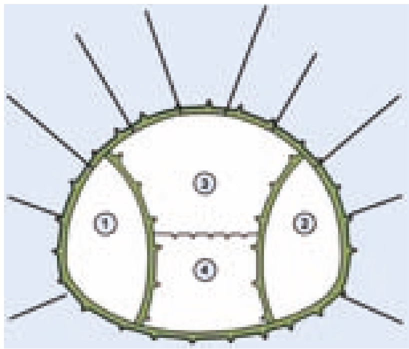


*Fig. 5: drift wall advance:
preceding drift walls (1, 2), followed by excavation of the crown 3) then the bench and invert (4) including safe support in each case*

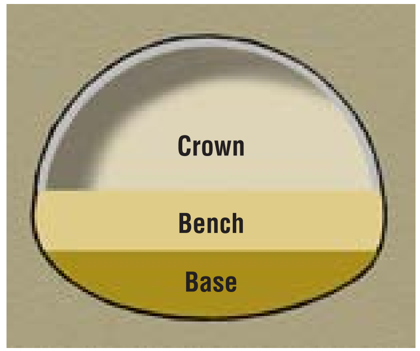


Fig. 6: methods of advance

3.1.1 Stabilisation

Sprayed concrete is the perfect material for excavation stabilisation. Its unique flexibility in the choice of application thickness, material formulation (fibre), output capacity, very early strength development (dry and/or wet) and the ability to respray at any time makes sprayed concrete the complete material for excavation stabilisation.

A distinction is made between full excavation and partial excavation according to the load-bearing properties and stability of the substrate. Excavation is by drill and blast or mechanical methods. In line with the old saying about tunnelling: “It is dark in front of the pickaxe”, preliminary bores or narrow pilot tunnels often precede the main construction in difficult ground conditions. These exploration tunnels are then incorporated in the excavation of the future tunnel or used as parallel tunnels for many different purposes. In all these applications sprayed concrete is used for stabilisation if the excavated face is not sufficiently stable. A thin base course in the form of a fine skin can be built up very quickly with sprayed concrete. If the load-bearing properties of the sprayed concrete are not sufficient, it is strengthened with reinforcement (fibre/steel reinforcement). By using

Fig. 7: shield heading machine operated by the joint venture for the Munich underground rail network, package U2, with spray manipulator moved upwards as additional stabilisation system

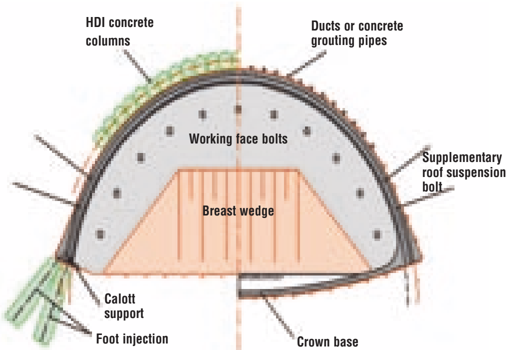


Fig. 8: rock supporting measures

3. Uses of sprayed concrete

steel rings and mesh, sprayed concrete becomes the lattice material between the beams. By using bolts, the load-bearing properties of the sprayed concrete skin can be linked to the increased load-bearing properties of the substrate near the excavation. If there is high water penetration and/or heavy fracturing of the rock, injection and preliminary waterproofing with gunite and drainage channels will create the conditions for applying the sprayed concrete layer.

Like all construction methods, underground construction has evolved historically on a regional basis. What is different about building underground is the varying geological conditions in the different regions. Because of this and the variety of projects involved (in cross section and length), different methods have developed. In partial excavation, these are basically the new Austrian Tunnelling Method (ATM), the German core method and the Belgian underpinning method. The full section is divided into smaller sections which are each temporarily stabilised and are only joined to form the full section at the end. In the full excavation application, partially and fully mechanised tunnel systems have a huge potential for development. In the longer term the constraints on use will be reduced solely to the economics of tunnel boring machines (TBM). Sprayed concrete application systems will be permanently installed on tunnel boring machines.

Fig. 9: excavation profile

Fig. 10: core method Uetliberg

3.1.2 Lining

The final lining of a tunnel is the permanently visible visiting card of the tunnelling contractor. The exception is a final lining with panelling. Inner lining concrete (shell concrete) and sprayed concrete are both used for a durable final lining. The higher the specifications for the evenness of the concrete finish, the more likely it is that a lining of structural concrete with interior ring forms will be used. Formed interior finishes are also considered to be aesthetically superior. Although new and additional installations are necessary on a large scale for this lining, the cost can be offset by the economics of the interior ring concrete, depending on the length of the project. This work demands massive inner ring moulds and the machine technology for concrete delivery, compaction and moving the forms. Conventionally produced concrete requires considerable compaction work because inner lining concrete generally has a substantial wall thickness. Accessibility is usually difficult, which means that so-called form vibrators are used, although they have a limited

Fig. 11: TBM-spraying robot with telescoping spraying boom

depth effect and are therefore very labour-intensive and subject to wear, which also results in significant additional noise pollution. An important innovation may be the use of self-compacting concrete (SCC) which replaces the whole mechanical compaction process and has a free-flowing consistency which enables to fill these forms completely.

Without the maximum evenness specifications, sprayed concrete is also suitable for the final lining. Before installation of the waterproofing membrane, the sprayed concrete surface is often levelled as smoothly as possible with a finer gunite, which greatly improves the conditions for laying the waterproofing membranes without wrinkles.

Durable final lining (construction method)	**Advantages of method selected**
Sprayed concrete lining	Use of existing installation from sprayed concrete application: - better economics in shorter tunnels - no additional installations Form the final lining together with the stabilisation: - Saving one full operation
Inner lining concrete	Much greater evenness accuracy in the concrete finish: - compressed air conditions in the tunnel - better visibility - more attractive appearance - simpler installation More clearly controlled homogeneity of the concrete quality without the spray application parameter Without the “very early strength“ requirement, more options in the concrete mix for durability requirements

Comparison of sprayed concrete and inner ring concrete final lining

4.1 Sprayed concrete requirements

This chapter describes all the requirements for sprayed concrete and mortar in a simple and easily understandable way. Armed with this information, the materials can be selected correctly. Basically, this involves choosing between the wet or dry spraying process, the right mix design and the right weighting of early strength development and durability of the sprayed material, based on the requirements.

4.1.1 Base materials

Concrete is a system of three materials, cement, aggregate and water. To extend its properties and potential applications, it can easily become a system of five components, resulting in complex interactions, especially when combined with the application parameters for sprayed concrete. Therefore it is important with sprayed concrete not to change too many parameters at the same time during the testing phase. Only the technically correct and economically viable solution will satisfy everyone.

4.1.1.1 Cement

The cement in the sprayed concrete mix acts as a "glue" which binds and embeds the aggregate particles together through the cement matrix. The cement is also the main lubricant for delivery of the sprayed concrete. Cement is hydraulic setting and therefore partly responsible for the mechanical properties of the set concrete. However, here there is an additional central requirement over and above its use in structural concrete. Cement for sprayed concrete must always start to set extremely quickly and give high very early strength.

Cement which does not react well when combined with setting accelerators or with slow-reaction admixtures in combined cements is not particularly suitable for the production of sprayed concrete for stabilisation.

The total fines content of a sprayed concrete mix depends on many different factors and can be assessed as follows.

Aggregate	0 – 8 mm	0 – 16 mm
Round	500 kg/m^3	450 kg/m^3
Crashed	525 kg/m^3	475 kg/m^3

Table of total fines content in one m^3 sprayed concrete

4.1.1.2 Additives

Additives are used in sprayed concrete for a variety of requirements and therefore differ considerably in characteristics:

- to supplement the fines balance ≤ 0,125 mm (filler)
- to improve specific durability properties (strength/resistance to solvent or driving forces)
- to increase the water retention capacity (mix stabilisation)
- to reduce the pump pressure during delivery (lubricant)

Many different types of fines are used. An important factor in selection of admixtures is the economy and therefore local availability of these very fine materials, which is why different types are preferred in different localities.

Effect	Additives type	Remarks
Hydraulic	Cement	Cement-type and -quantity influence the workability and strength development
Latent hydraulic	Slag	Slow down the strength development and increase the durability
Pozzolanic	Microsilica Fly ash	Improve the durability, increase the bonding behaviour and with it the mechanical properties . Reduce the pH value of the concrete intersitional water and should therefore be limited in quantity.
Inert	Stone dust (e.g. limestone filter)	Do not themselves develop strength but help by improving the particle matrix

Effects of additives for sprayed concrete and mortar

Microsilica
Silicafume is amorphous SiO2, which occurs as a by-product in the production of silicon. The materials, have an enormous specific surface and are highly reactive and therefore technically suitable for a variety of requirements. They do not adversely effect the early strength. Silicafume is the ideal additives, but the cost is high.

Fly ash
Fly ash is obtained from the electric filters in electricity generation with pulverized coal. Fly ash is cheap and has very good workability properties. Fly ash is also suitable for specific durability requirements. The homogeneity of the product is an important factor with fly ash.

Slag
Slag occurs during smelting of iron ore. It is again cheap and an excellent filler, but reduces very early strength properties. The durability of sprayed concrete can often be improved with slag.

Characteristic	Cement	Silicafume	Fly ash	Slag	Stone filler
Fresh conrete characteristics					
Handling	+ +	+ +	+ + +	+	+ + +
Water retention capacity	+ +	+ + +	+	+	+ + +
Strength development					
Very early strength up to 4 h	+ + +	+	-	-	+ / -
Early strength up to 12 h	+ +	+ +	-	-	+ / -
Final strength	+ +	+ + +	+ +	+ + +	+ / -
Durabiliy					
Water resistance	+ +	+ + +	+ +	+ +	+
Sulphate resistance	-	+ +	+ / -	+ + +	+ / -
AAR resistance	-	+ / -	+ / -	+ + +	+ / -

Characteristics of additives in sprayed concrete and mortar

4. Sprayed concrete technology

4.1.1.3 Aggregates

The aggregates (stone particles) form the framework of the sprayed concrete matrix. Approximately 75% of the volume consists of the sand and gravel components. The geological composition of the aggregate has a huge influence on the workability and hardened concrete properties. Aggregates have many different functions:

- main parameter influencing the homogeneity of the sprayed concrete mix
- initial parameter determining the water requirement
- economic filler in the sprayed concrete matrix
- achievement of the mechanical properties (tensile strength in bending and compressive strength)
- strong influence on the workability of the mix (particle forms and fines)
- high influence on the durability required (porosity and purity)

For all these reasons the aggregate must be given the highest priority, which sadly is not always the case. If the ≤ 0.125mm fines content changes by just a few percent, a mix which is extremely workable can soon become one that is impossible to pump. Or if the percentage of soft components in the aggregate is too high, its frost resistance can be totally destroyed. As far as concrete technology is concerned, generally speaking grading

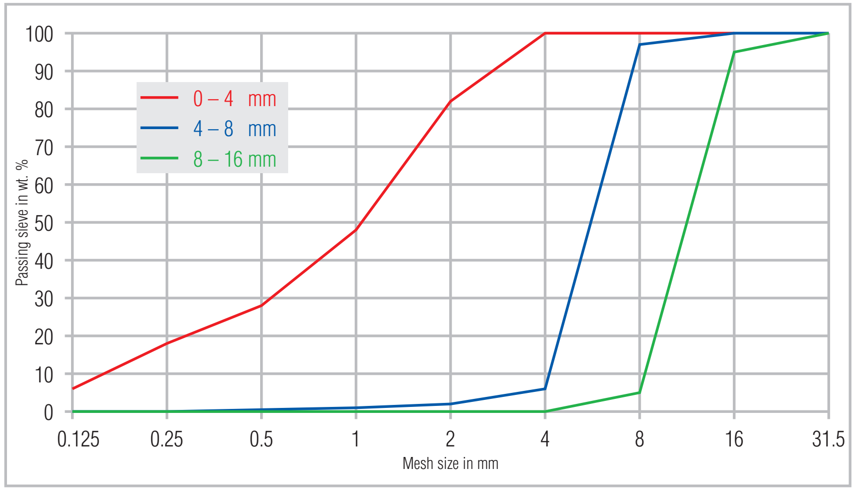


Fig. 12: Particle size distribution of individual components

distribution curves with a maximum aggregate particle size of 16 mm are good, but in terms of the overall sprayed concrete application process, particle sizes of up to 8 mm offer advantages. Grading curves for dry and wet sprayed concrete applications are shown.

4.1.1.4 Water

Water goes into the sprayed concrete as added water during its production and as inherent moisture in the aggregate. The consistency (plasticity) of the mix is regulated by the water and the sprayed concrete admixtures. The mix water must not contain any constituents that slow down or speed up the hydration. These are mainly:

- oil and grease
- chlorides
- sulphates
- sugars
- salts

Water occurring naturally such as groundwater, rainwater, river water and lake water is normally suitable. Sea water should not be used due to its high chloride content. Drinking water is always suitable for the production of sprayed concrete.

4.1.1.5 Sprayed concrete admixtures

Concrete admixtures are used to improve and/or change concrete properties which cannot, or cannot correctly, be controlled by the cement, aggregate and water components. Admixtures are also added to sprayed concrete during the spraying process to regulate the start of setting. Concrete admixtures and additives make concrete a complex multi-material system.

Sprayed concrete admixtures are added as a percentage of the cement, measured by weight or volume. They are added in an approximate range of 0.5 % to 6.0 %. This gives quantities of 2 kg/m^3 to 30 kg/m^3, that is in the range of thousandth parts of the total concrete volume. All the admixtures used are fed into the concrete during its production at the mixing plant after the initial water metering. Main exception is the setting accelerator, which is adding immediately before spraying.

4. Sprayed concrete technology

Sprayed concrete target specifications	Control parameters	Concrete admixtures for target achievement
Compressive strength Tensile strength in bending Durability	Set concrete characteristics	Flow control agents FM Admixtures Additives Fibre reinforcement Curing agents
Pumpability Sprayability Spraying configuration	Workability	Mix stabilisers ST Additives
Working time Strength development	Open time (working time) Setting time (stiffening acceleration)	Setting accelerators Setting retarders Additives

Target specifications for the use of sprayed concrete and mortar additives

The ecology and safety of sprayed concrete admixtures are evaluated and classified by the EFCA (European Federation of Concrete Admixtures) quality mark.

The various sprayed concrete admixtures are listed below and their properties are described.

www.fshbz.ch
www.efca.info

Accelerators:
Accelerators control the start of setting of the sprayed concrete after it is applied. Accelerators are used in powder or liquid form. An important criterion for the quality of the set sprayed concrete is constancy of accelerator dosage, which is why using accelerators should always be added from metering units that guarantee quantity uniformity matching the output (synchronisation). In quality terms the only exception is minor applications. Setting accelerators are categorized according to their chemical composition and therefore their individual mode of action and effect on the setting of concrete.

Property	Accelerator type		
	Alkaline Aluminate-based	Alkaline Silicate-based	Alkali-free
Dosing range	3 – 6 %	12 – 15 %	4 – 7 %
pH value	13 – 14	12 – 13	3
Na_2O equivalent	20 %	12 %	< 1 %
Very early strength at same dosage	++++	++++	+++
Final strength	+	--	+++
Watertightness	++	--	+++
Leaching behaviour	---	--	-
Occupational health	---	-	+++
Occupational and transport safety	--	-	+++

Type	Product	Use/effect	Remarks
Liquid, alkali-free setting accelerator	*Sigunite® AF Liquid*	• Heading stabilization in tunnelling • Rock and slope stabilization • High-quality lining shotcrete • Very high early strength • Increased watertightness • Reduced eluate quantity • Better health and safety	• For the dry or wet spraying process • Non-corrosive • Low final strength reduction compared with the non-accelerated original concrete • Not compatible with alkaline accelerators • Metal parts in contact with this accelerator must be of stainless steel
Powder, alkali-free setting accelerator	*Sigunite® AF Powder*		
Liquid, alkaline setting accelerator	*Sigunite® AF Liquid*	• Heading stabilization in tunnelling • Rock and slope stabilization • Very high early strength • Lower rebound • Can be sprayed on a wet substrate	• For the dry or wet spraying process • Corrosive • Final strength reduction compared with the non-accelerated original concrete
Powder, alkaline setting accelerator	*Sigunite® AF Powder*		

Table of the various accelerator types and their main properties

It is clear from this table that only alkali-free setting accelerators should be used for durable, high-quality sprayed concrete, taking account of the safety of the spraying team. Alkali-free setting accelerators offer improved safety and security in many areas:

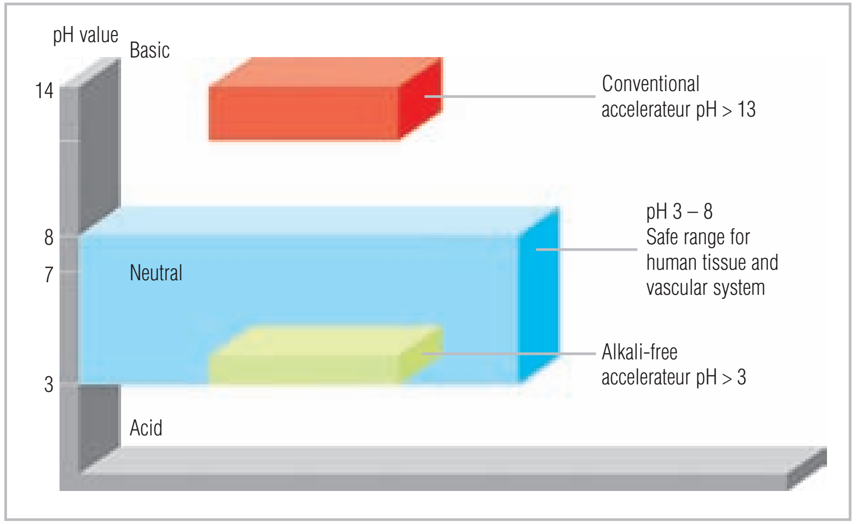


Fig. 13: List of setting accelerators

- *Safe working:*
  Due to the pH value of approx. 3, no caustic water spray mist and aerosols occur in the tunnel air and therefore there is no damage to skin, mucous membranes and eyes.
- *Safe environment:*
  With the use of alkali-free accelerators, additive particles with a high alkaline content are not discharged into ground and drainage water.
- *Safe handling:*
  Alkali-free setting accelerators are not a hazard during transport, storage, decanting or dosing

- *Secure concrete quality:*
  The use of alkali-free setting accelerators minimises the effect of the concrete hardening and improves the tightness of the sprayed concrete and therefore its durability.
- *Safe disposal:*
  Alkali-free setting accelerators do not introduce any additional soluble alkalis into the concrete. This greatly reduces the risk of drainage infiltration.

- Accelerators are defined as alkali-free if the alkali equivalent content based on the weight of the accelerator is ≤ 1%.
- Products are defined as alkaline if their pH value is between 7 and 14.

Sprayed concrete admixtures:
Whereas the very early and early strength of sprayed concrete is controlled by setting accelerators directly at the nozzle, the other additives are dosed during its production at the mixing plant. Liquid products should be added with the approximate water dosage at the earliest. Admixtures are even more effective if they are added later with the mixing water. The wet mixing time to achieve the full effect of the material depends on the effect achieved and the chemical composition of the products. As a rule, a mixing time after admixture dosing of > 60 sec is sufficient. Some products such as air entraining agents need a minimum of 90 seconds, but these are rarely used in sprayed concrete. Admixtures are mainly used in sprayed concrete to improve the set concrete properties (quality) and control the fresh concrete properties (workability/working time). Many different products are available for this.

The most important products for use in sprayed concrete are flow control agents and admixtures to retard the start of hydration.

Flow control agents:
Better known to many as plasticizers or superplasticizers. Superplasticisers are used to control the specified water content (w/c ratio) while simultaneously guaranteeing the required fresh concrete consistency (plasticity). Two apparently dia-metrically opposed interests,

- a low water content (w/c ratio) to guarantee the quality and
- a plastic fresh concrete consistency for good workability of the mix

4. Sprayed concrete technology

Type	Product	Use/effect	Remarks
Superplasticisers	*Sika® Tard* *Sika® ViscoCrete®*	• High water reduction • Better workability • Time controlled workability • Rapid increase in strength • Better shrinkage and creep properties • Higher watertightness	• Optimum effect when added after the mix water • Optimum dosage depends on cement type • For specific properties, preliminary tests with the cement and aggregates to be used are essential
Retarder	*Sika® Tard-930*	• Adjustable workability • No cleaning of pumps and hoses necessary during the retarding phase	
Silicafume slurries Silicafume powder	*Sikacrete®-L* *SikaFume®*	• Improved fresh concrete homogeneity • Much higher watertightness • Improved adhesion between aggregate and hardened cement • High frost and freeze/thaw resistance • Lower rebound	• Added at the batching plant • Optimum curing is necessary because silicafume concrete dries out very quickly on the surface
Polymer-modified Silicafume powder	*Sikacrete®-PP1*	• As for *SikaFume,®* plus: • Significant water reduction • For very high quality specifications	• As for *SikaFume®*
Pumping agents and stabilizers	*SikaPump®* *Sika® Stabilizer*	• Improvement in homogeneity and internal cohesion for unsuitable concrete mixes • Increase in spraying output with lower energy consumption, even for mixes with crushed aggregate	Addition increases the power input of the mixer and the concrete consistency – do not adjust by adding water

Summary table of sprayed concrete admixtures are achievable with superplasticisers, which control the workability by dispersion on the fines in a sprayed concrete mix instead of water. Flow control agents of different generations exist and differ in their level of performance on water reduction capacity and processing characteristics. Unlike plasticisers for conventional concrete, products for sprayed concrete must have a long open time and very good pumpability and be able to combine well with accelerators.

Consistency stabilisers/setting retarders:
Special products can be added to the sprayed concrete mix to control (retard) hydration. They allow the open time of sprayed concrete to be influenced almost at will, so that the workability does not have to be applied within 1 or 2 hours. The time can be adjusted according to the conditions by regulating the quantity of these retarders added. The properties of superplasticisers are often combined with the effects of this retarders.

Fig. 14: Equipment for measuring the setting conditions

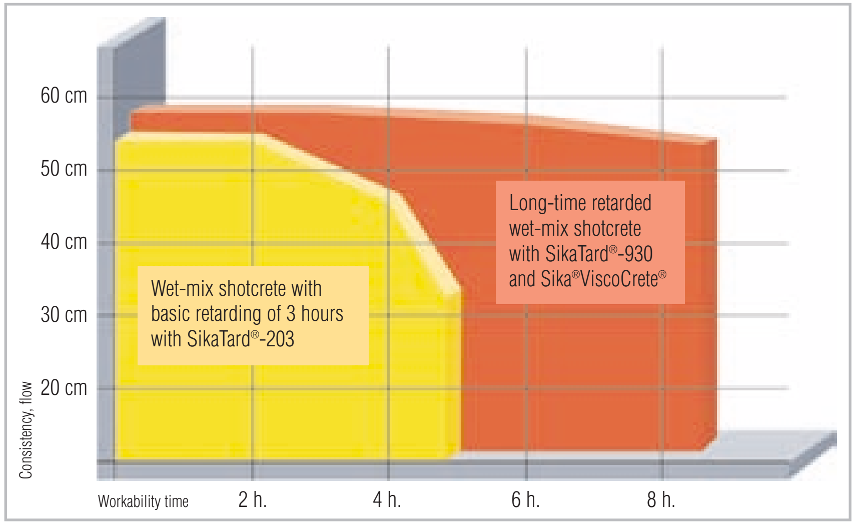


Fig. 15: Workability time of wet sprayed concrete mixes

Mix stabilisers:
To improve the workability (pumpability), special admixtures are often added to difficult mixes to overcome variations in the fines, a difficult form or poor water retention capacity of these ≤ 0.125mm components which are so important for processing. Stabilisers promote inner cohesion and supplement and improve the quantity of lubricant film.

Pump pressure with/without pumping agent

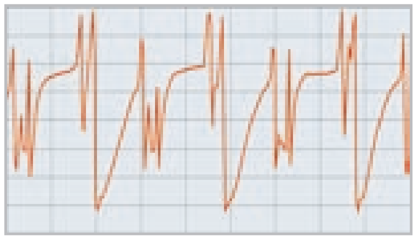


Fig. 16: without SikaPump®: uncontinuous pumping pressure

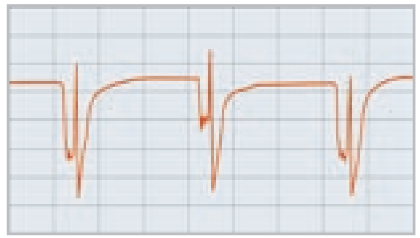


Fig. 17: with SikaPump®: continuous pumping pressure

4.1.2 Early strength development

Variable requirements for early strength development have to be met, depending largely on the point of use of the sprayed concrete or mortar. A distinction is made between:

- very early strength development in the range of a few minutes to about 1 hour
- early strength development in the range of about 1 hour to max. 1 day

After that we require of normal strength development, comparable with that of structural concrete. The strength development is influenced by the same factors:

- cement type and content
- water content
- temperatures in the concrete and the environment (substrate)
- layer thickness
- For sprayed concrete there is the added strong influence of the accelerator, which is intended to greatly increase the strength from the first few minutes to the first few hours.

Sprayed concrete is mainly used for stabilisation, but also frequently to grout or fill cavities. Mainly for rock and soil support and overhead spraying requirements for very early and early strength development are crucial and are generally specified.

Very early strength development
In the first few minutes after application of the sprayed concrete, the adhesive strength is decisive. Accurate dosage of the amount of air has here a great influence. It determines the rate of application (thickness). The consequence of insufficient air is insufficient concrete compaction which in its turn negatively influences final strength of the sprayed material. Too much air produces much dust and high rebound losses. Fine cement and accelerator particles lost in the dust are important components missing for optimal strength development. Dust emission must also be avoided as much as possible for reasons of work hygiene (health protection). In any case, it is never possible to apply more sprayed concrete than the substrate is capable of absorbing, even as initial tensile force on the surface. The very early strength development determines the speed of advance and therefore the performance of the contractor.

4. Sprayed concrete technology

Early strength development
A measurable compressive strength is obtained after about 1 hour (in special cases or in immediate stabilisation after only a few minutes). This strength development determines when heading can continue to advance. *The early strength development determines the progress with tunnelling.*

4.1.3 Final strength

Alongside the very early and early strength required specifically for sprayed concrete, there are mechanical requirements for the hardened sprayed concrete, just as there are for conventional concrete, generally after 28 days. The level of strength is based on the engineering by the design requirements. The compressive strength is measured on cores taken from the structure or from sprayed panels. Cube samples of the base concrete are sometimes used as controls, but they cannot give meaningful results for the sprayed concrete application because the characteristics may be changed considerably by the spraying process. The setting accelerators used and the skill of the nozzle man have a huge influence on the final strength obtained. Sprayed concrete is normally designed as a thin load-bearing skin and should therefore have ductile load-bearing properties. These can be obtained with reinforcing mesh, but the use of fibres for sprayed concrete and mortar reinforcement is ideal for flexible forming of the material. Steel-fibre-reinforced sprayed concrete is an extremely high-performance, load-bearing material.

The properties of the sprayed concrete are tested on samples taken directly from the structure or from panels sprayed parallel to the application under conditions of maximum similarity and then taken for sampling without destroying the structure. Sprayed panels with defined dimensions are also used for the plate test to determine the tensile strengths and the ductilty of the reinforced sprayed concrete.

4.1.4 Fibre-reinforced sprayed concrete

Fibre-reinforced sprayed concrete has now become much more important due to the development of new and more effective types of fibre, its increasing availability and its inclusion in various standards. It can be considered the perfect combination with sprayed concrete. Like conventional concrete, sprayed concrete is a brittle material with limited tensile and bending strength but very good compressive strength. It is certainly possible to reinforce sprayed concrete with conventional steel reinforcement, but its installation is very labour intensive, time-consuming and frequently in conditions that are still safety critical. Also, reinforcing bars are not well adapted to the flexible layer thickness design of sprayed concrete. This is why it makes sense to use fibre-reinforced sprayed concrete. Its main advantages are:

- homogeneous distribution of the fibre reinforcement in the sprayed concrete
- great improvement in the sprayed concrete ductility
- higher tensile strength in bending
- greater security due to high post-cracking strength
- increased impact resistance
- improved adhesive strength
- reduced early shrinkage cracking behaviour
- increased fire resistance

Fig. 18: failure surface of two prisms

Fig. 19: steel fibres

In principle, all fibre types and materials are suitable for sprayed concrete, where the material is used in tunnelling, steel fibre is generally most appropriate. Carbon fibre has ideal properties but is completely uneconomic for use in conventional sprayed concrete. Glass fibre is only suitable for special fine-particle applications and has to meet special requirements for its long-term behaviour. Polymer fibre is mainly used for concrete repairs because it improves the internal cohesion of the sprayed concrete and reduces shrinkage cracking during early strength development. Plastic fibre improves the fire resistance of concrete in general. Modern generations of plastic fibres are now appearing in the traditional steel fibre applications.

Steel fibre surposses reinforcing bars and mesh on cost-performance in nearly every case.

The following guidelines apply to fibre-reinforced sprayed concrete production:

- The fresh concrete consistency must be more plastic so that the fibre-reinforced sprayed concrete can be pumped.
- Due to the larger surfaces, the lubricant and adhesive film requirement is greater and therefore the binder content must be increased.
- The adhesive properties are improved by the use of silicafume.

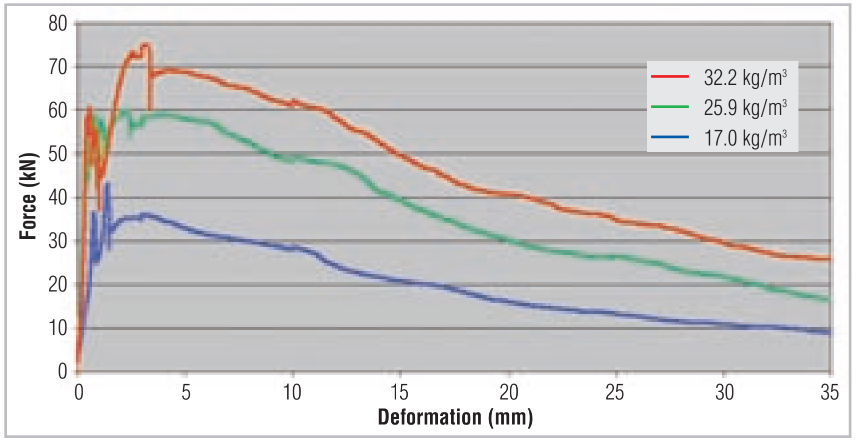


Fig. 20: plate test SIA 162/6, Steel fibre Dramix RC-65/35-BN

- The point for adding the fibre depends on the type of fibre and can be changed if problems occur (e.g. spiking).
- Remember that fibres are also lost with the rebound and therefore the content and efficiency of the sprayed concrete are the determining factors, not the theoretical steel fibre dosage.

4.1.5 Sprayed concrete with increased fire resistance

The increased fire resistance of sprayed concrete and mortar can be improved by complex mix formulations. These materials are generally supplied as ready mix mortars and are very expensive. It is then possible to meet virtually any fire resistance specification. To obtain these formulations, all the components must be selected for their fire resistance, which results in specific solutions for the aggregate in particular.

However, the fire resistance can also be considerably improved at low cost by including a wearing course. By adding a special plastic fibre (PP fibre), the temperature drop in a thin wearing course can be guaranteed; it has to be replaced after a fire.

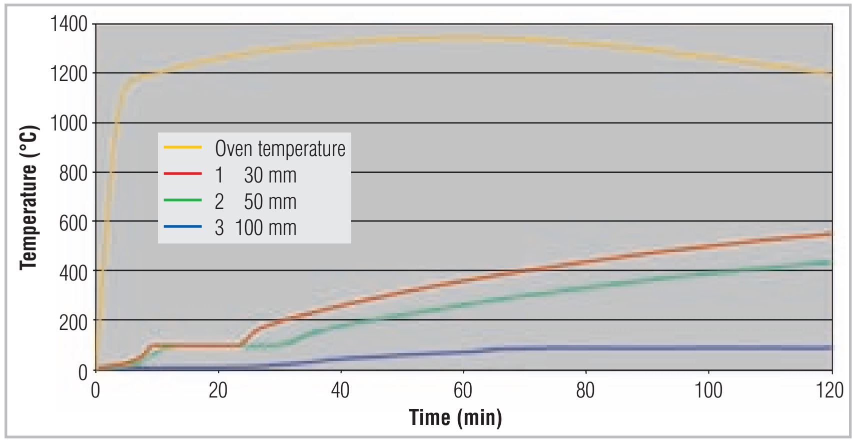


Fig. 21: Fire resistant sprayed concrete with PP fibres tested by the RWS / TNO specification

4. Sprayed concrete technology

4.1.6 Durability

The amount of water in a mix greatly affects all the properties of the hardened concrete and is the main factor for durability. In sprayed concrete too: the lower the water content in the mix, the better the durability of the material, but only if combined with adequate curing The measure for analysis is the water to cement ratio or water to binder ratio. The ratio is most influenced by the aggregate and allowance must be made for the stone available when specifying the water content limits.

- **water/cement ratio ≤ 0.55 for concrete with a low specification**
- **water/cement ratio ≤ 0.50 for concrete with an average specification**
- **water/cement ratio ≤ 0.46 for concrete with a high specification**

Along with the water content, the aggregate and binder naturally influence durability. Sprayed concrete is also subject to the influence of the rapid very early and early setting, which is usually controlled by a setting accelerator or special cement. Traditional setting accelerators reduce the final strength. This is another reason for preferring the use of alkali-free accelerators for the production of durable sprayed concrete. The use of silica-fume also gives additional compaction of the concrete microstructure and increases the adhesive strength between the aggregate and the hardened cement matrix. Both improve the durability significantly. Correctly formulated sprayed concrete is capable of meeting all the durability requirements, just like conventional concrete.

As with conventionally placed concrete, so also with sprayed concrete: The final sprayed concrete is only as good as its curing. However, the curing process is far more difficult, mainly because drying and draughts act on the sprayed concrete surface during the first few hours, when formed concrete is protected by the shuttering. Regular wetting of the surface helps, but this is very hard to carry out in practice in the tunnel section. Covering, for example with a mobile curing machine, is also difficult in sprayed concrete construction. Products called internal curing agents have recently come onto the market; they can be added to the sprayed concrete during production and when integrated perform the curing function.

Component	Designation	Product	Content
Binder	CEM I 42,5 oder CEM I 52,5 CEM III / A 32,5 oder CEM II / A-D 52,5		430 kg/m³
	Silicafume	*SikaFume®*	30 kg/m³
Aggregate	Sand 0 / 4 mm round / crushed		60 %
	Gravel 4 / 8 mm round / crushed		40 %
Water content	W/C	0,46	211 l/m³
Sprayed concrete additives	Superplasticiser	*Sika® ViscoCrete®*	1,20 %
	Retarder	*Sika® Tard*	0,30 %
	Pumping agent	*SikaPump®*	0,50 %
	Accelerator	*Sigunit®-L-AF*	3,00 % to 6,00 %

Mix design example for high performance sprayed concrete

Target parameter	Measure	Product
To increase compressive strength	• Reduced water content • Use of silicafume	*Sika® ViscoCrete® FM* *SikaFume®-TU*
To improve waterproofing	• Reduced water content • Use of silicafume	*Sika® ViscoCrete® FM* *SikaFume®-TU*
To increase frost resistance	• Reduced water content • Use of silicafume	*Sika® ViscoCrete® FM* *SikaFume®-TU*
To increase sulphate resistance	• Reduced water content • Use of sulpate-resistant CEM and/or use of silicafume • Minimised accelerator dosage	*Sika® ViscoCrete® FM* *SikaFume®-TU* *Sigunit® L-AF*
To increase AAR resistance	• Reduced water content • Use of binder with low Na_2O equivalent • Use of aggregates with low AKR potential • Minimised accelerator dosage	*Sika® ViscoCrete® FM* *Sigunit®-L-AF*

Measures to change sprayed concrete characteristics

As with any human activity, the quality of the installed sprayed concrete is largely determined by people, in this case the nozzle man and the shift supervisor. None of the preliminary measures can achieve their purpose unless they are correctly implemented on site. But the operatives must be given the appropriate conditions in which to work.

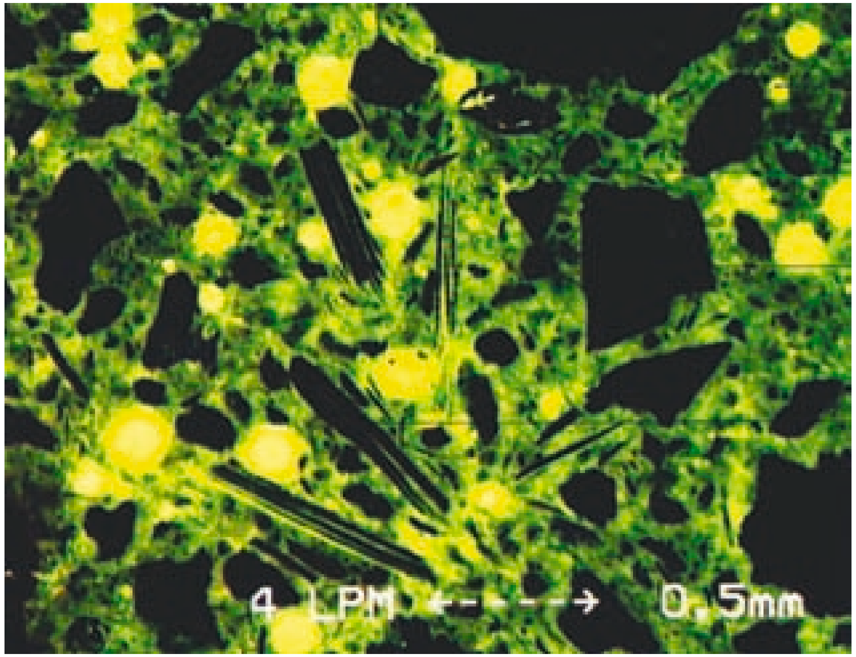


Fig. 22: Thin section analysis, LPM AG Switzerland

4.2 Wet sprayed concrete

Wet sprayed concrete means delivery (handling) of a ready-mixed sprayed concrete consisting of aggregate, cement, water and sprayed concrete admixtures in a workable mix. For spraying, the wet sprayed concrete is mixed with air and setting accelerators and then applied. The wet sprayed concrete can be processed by the dense-flow or the thin-flow method. Dense-flow sprayed concrete is the latest high-performance process.

4.2.1 Uses

Wet sprayed concrete is always used when high set concrete quality is specified and high output is required. This process is by far the most popular in mechanical tunnelling. Ultimately the choice of process is also determined by the contractor's preferences!

The main applications of the wet sprayed concrete process are

- sprayed concrete works with high output capacity
- substantially improved working conditions in the spraying area
- higher durability due to controlled mixing water quantity

4.2.2 Advantages

The advantages of the wet spraying process cover many different areas. Wet sprayed concrete is the more modern and efficient method.

- increased spraying output, up to 25 m^3/h in some cases
- rebound level reduced by a factor of two to four
- substantially improved working conditions due to less dust generation
- reduced wear costs on the spraying equipment
- low air requirement during spraying
- higher quality installed sprayed concrete (constant water content)

Wet sprayed concrete by the dense-flow process demands more work at the beginning (start-up) and end (cleaning) of spraying than the dry process. Also, the working time is preset during production and the sprayed concrete must be applied within that time, otherwise concrete can be wasted.

4.2.3 Wet sprayed concrete mix design

The mix design of wet sprayed concrete depends on the specification requirements and the workability expected, in other words the following parameters:

- the set concrete target specifications (compressive strength/durability)
- the logistics concept to be used (handling methods/temperature conditions)
- the specified installed material conditions (very early and early strength development)
- the economics of the wet sprayed concrete mix

It is as a result of all these parameters that the cement type and content, aggregate type and grading, water content and type and quantity of sprayed concrete admixtures are selected and confirmed by tests or adapted after evaluation of the target parameters. Typical wet sprayed concrete formulations are shown in detail below.

In the case of aggregate particle sizes, the aggregates available locally are the main factor determining the choice of grading curve. The curve that best meets the requirements listed must be established by testing and experience with the granular material available. Replacement of the aggregate is only an option in exceptional circumstances due to the economics (transport of huge quantities). The diagrams below give examples to define the grading curve based on screening of the individual components.

Wet-mix shotcrete 0 – 8 mm dense-flow process		
Cement	425 kg	135 l
SikaFume®-HR/-TU	20 kg	9 l
Sika® Tard (FM) / Sika® ViscoCrete® (FM)	1.2 %	
Sika® Tard-930 (VZ)	0.3 %	
Aggregate: 0 – 4 mm with 4 % inherent moisture (60 %) 4 – 8 mm with 2 % inherent moisture (40 %) Added water (W/C = 0.47) Air voids (4.5 %) Steel fiber	 967 kg 791 kg 155 kg 40 kg	 358 l 293 l 155 l 45 l 5 l
Shotcrete **Density per m³**	 **2398 kg**	**1000 l**
1 m³ applied shotcrete gives set on the wall Accelerated with *Sigunit® AF Liquid* (rebound 6 – 10 %) 0.90 – 0.94 m³ Cement content in shotcrete 450 – 470 kg/m³ Steel fiber content in shotcrete appr. 30 kg/m³		

Wet sprayed concrete mix design, dense-flow process

Wet mix shotcrete 0 – 8 mm thin-flow process		
Cement	400 kg	127 l
Sika® Tard (FM) / Sika® ViscoCrete® (FM)	1.2 %	
Sika® Tard-930 (VZ)	0.3 %	
Aggregate: 0 – 4 mm with 4 % inherent moisture (50 %) 4 – 8 mm with 2 % inherent moisture (50 %) Added water (W/C = 0.47) Air voids (4.5 %)	 891 kg 891 kg 168 kg 	 330 l 330 l 168 l 45 l
Shotcrete **Density per m³**	 **2350 kg**	

Wet sprayed concrete mix design, thin-flow process

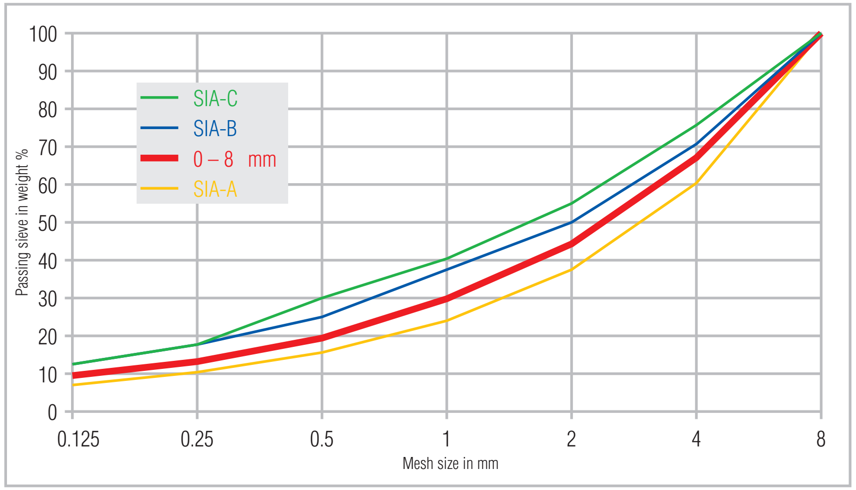


Fig. 23: grading curve of wet sprayed concrete, dense-flow process

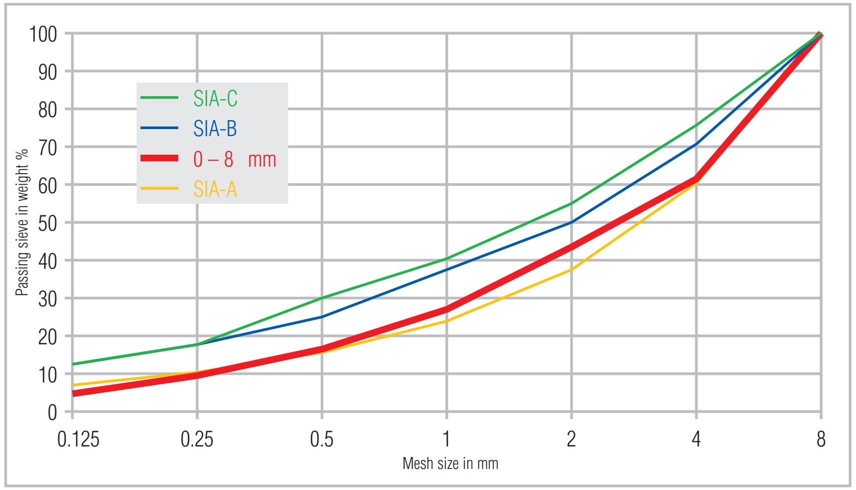


Fig. 24: grading curve of wet sprayed concrete, thin-flow process

4.2.4 Quality assurance

A quality assurance plan must be produced by the contractor as part of the qualification tests (initial testing) and also for the regular quality assurance. It must include all the relevant quality and reliability parameters in a logical form and should be structured in a practical way that results in economic working and therefore implementation of the plan. The quality assurance should define the whole process.

Process	Stage	Test parameter	Frequency
Components	Aggregates	Moisture Grading curve Particle composition	Each delivery/batch Periodically Periodically
	Cement / admixtures	Delivery documents	Each delivery/batch
	Concrete additives	Delivery documents	Each delivery/batch
Concrete production	Mixing plant	Weighing/mixing tool	To maintenance plan
	Concrete production	Production consistency (Mixer load)	Each delivery/batch
		Fresh concrete inspection Water content Fresh concrete density Temperatures (concrete/air) Consistency Air content	Periodically
Transport	Hauling equipment	Maintenance	To maintenance plan
Application	Sprayed concrete unit	Maintenance: Wearing parts Air/concrete Accelerator dosage	To maintenance plan
	Sprayed concrete	Consistency Very early strength Early strength Final strength Durability	Daily To test plan according to concreting rate To test plan according to concreting rate To test plan according to concreting rate To test plan according to concreting rate

Quality assurance

4. Sprayed concrete technology

4.3 Dry sprayed concrete

Dry sprayed concrete means delivery (transport) of a ready-mixed sprayed concrete consisting of aggregate, cement and any sprayed concrete admixtures but without mixing water. This ready-mixed formulation is either completely dry (dust dry) or is dampened by the inherent moisture in the aggregate. For the spraying operation, the dry sprayed concrete is mixed with water and setting accelerators and then applied. Instead of setting accelerators, special rapid-hardening cements that set in a very short time after wetting with water can be used in the dry spraying process. The thin-flow process must be used for delivery of dry sprayed concrete. Dry sprayed concrete is a process that has long proved successful but is being continuously developed and improved.

4.3.1 Uses

Dry sprayed concrete is always used when smaller quantities and outputs are required and high very early strength is essential, for example for preliminary sealing against high water penetration with gunites. The final, the choice of process is also determined by the contractor's preferences!

Applications for dry sprayed concrete and ready-mixed gunites:

- concrete repairs
- preliminary sealing against high water penetration
- minor spraying works
- waterproofing works
- logistics concept not time dependent (local storage)

4.3.2 Advantages

The advantages of dry sprayed concrete lie in its flexibility. It is the traditional method of applying sprayed concrete, better known throughout the world.

- high very early strength for preliminary sealing or stabilising
- almost unlimited holding time (availability) of silo stored material
- no concrete waste

With dry sprayed concrete, the economics are affected by the high rebound quantities and dust generation and the higher wear costs.

4.3.3 Dry sprayed concrete mix design

The mix design of dry sprayed concrete again depends on the requirements. However, apart from the early strength requirements, adaptation to optimise the dust generation and rebound quantity is essential for the economic use of dry sprayed concrete.It is as a result of these parameters that the cement type and content, aggregate type and grading, water content (inherent moisture) and type and quantity of sprayed concrete admixtures are selected and confirmed by tests or adapted after evaluation of the target parameters. A typical dry sprayed concrete formulation is shown in detail below.

In the case of stone particle sizes, the aggregate available locally is the main factor determining the choice of grading curve. The curve that best meets the requirements listed must be established by testing and experience with the granular material available. Oven-dried ready-mixes from sprayed mortar producers are often used In dry sprayed concrete

Dry-mix shotcrete 0 – 8 mm	
Cement	280 kg
SikaFume®-HR/-TU	20 kg
Sika®Tard-930 (VZ) 0,3 % 55 % 0 – 4 mm with 4 % inherent moisture	ca. 680 kg
45 % 4 – 8 mm with 2 % inherent moisture	ca. 560 kg
Dry mix moist m³ *must be checked by a yield test	***ca. 1540 kg**
Cement content For 1000 litres dry mix, 280 kg cement is added to 800 litres aggregate For 1250 l litres dry mix, 350 kg cement is added to 1000 litres aggregate	
Shotcrete from 1 m³ dry mix gives on the wall Accelerated with *Sigunit®AF Powder* (rebound 16 – 20 %) 0.58 – 0.61 m³ Accelerated with *Sigunit®AF Liquid* (rebound 20 – 25 %) 0.55 – 0.58 m³ Cement content in the shotcrete appr. 450 kg/m³	

Dry sprayed concrete mix design

4. Sprayed concrete technology

and particularly for dry sprayed mortar applications, i.e. gunites. These gunites are supplied in bags or by silo equipment and are stored in an intermediate silo before use, so that the site is not dependent on the aggregate obtainable locally. For production on site, the diagram below can be used to define the grading curve based on screening of the individual components.

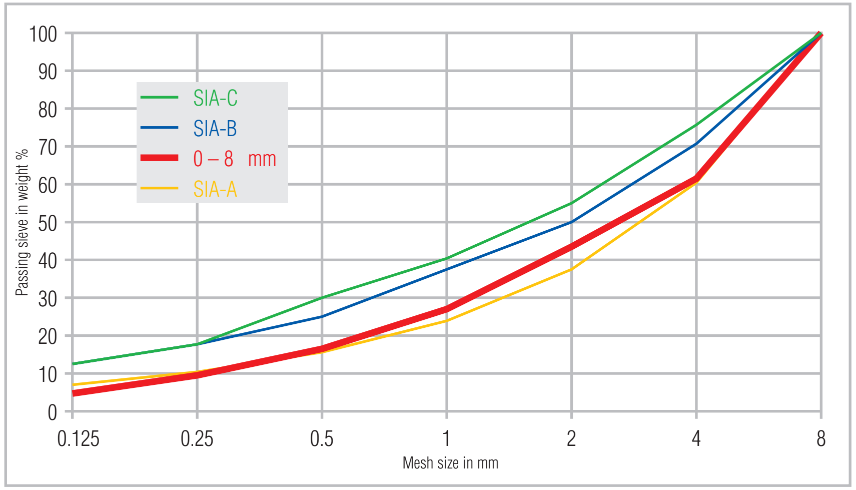


Fig. 25: dry sprayed concrete grading curve

4.3.4 Moisture content of aggregates

In the dry process, the inherent moisture presetting is very important for dust generation and pumpability. If the material is too dry, large amounts of dust are generated. On the other hand, if the material is too wet, blockage (clogging) occurs in the pumping system. The inherent moisture content of aggregates should be between 2 % and 5 % and is either controlled by the moisture in the granular material or obtained by means of special wetting installations. Dry mix produced locally at the mixing plant always has some inherent moisture because the aggregate can only be kept completely dry with a great deal of effort. Ready for use mortar and sprayed concrete produced in a dry material plant is as dry as dust and must be prewetted to reduce the dust generated.

5. Sprayed concrete applications

5.1 Safety

Safety is a central concept throughout the building industry, but particularly in sprayed concrete construction because it combines high-powered machinery (hydraulic/pneumatic/electronic) with a method of application in which the concrete is projected through the air! Its users and people in the immediate vicinity must be protected. The hazards are:

- **Transportation** of the sprayed concrete in large vehicles, usually in confined spaces with poor lighting: Personal precautions include standing well clear early enough; wearing high-visibility protective clothing; adequate lighting on the vehicle (and cleaning it); reversing alarm signal

- **Transfer** of the concrete to the conveyor: Guard to prevent access to the conveyor unit; personal protective equipment (important: splash protection for eyes)

- **Conveyance** of the sprayed concrete, air and setting accelerators to the point of application: Regular servicing of the equipment according to the maintenance plan (particularly checking the conveyor tubes or hoses); appropriate employee technical training of the mechanics; personal protective equipment; adequate site lighting

- **Application** of the sprayed concrete: Personal protective equipment (impact-resistant goggles, helmet, gloves, breathing apparatus, ear defenders, safety boots, full body clothing); no entry to unprotected, freshly sprayed areas; adequate lighting

- **Personnel not involved** should not be in the vicinity of the spraying operations. If they are, they must wear the same personal protective equipment

The most serious hazards are without doubt the risk of fresh sprayed concrete or unstabilised substrate falling onto workers, misuse of electrical, hydraulic and pneumatic equipment and installations and carelessness, especially forgetting to put on items of personal protective equipment such as safety goggles.

5.2 Sprayed concrete substrate

The bond between the sprayed concrete and the substrate can only be as good as the quality of the two contact faces. Due to its binder content and high jet impact speed, sprayed concrete has the right conditions for strong keying and high adhesive strength. Therefore the other face of the contact point, the substrate, is generally the key factor in bonding. In the case of concrete blinding, it must be roughened, which is generally obtained with a rough sprayed concrete finish. The surface must also be free from loose parts with low adhesion. The surface must be wetted to prevent the bond area drying out due to the absorption effect of the dried blinding concrete. The same applies in principle to fresh excavation surfaces. The force of the cleaning operation depends on the internal cohesion of the substrate and the water requirement is based on the inherent moisture of the adherend surface. The substrate must always be free from dust.

- clean the contact surface (dust/loose sections)
- wet the substrate (according to the substrate absorbency)
- apply the sprayed concrete/mortar correctly (perpendicular to the substrate)

To optimise the operations, the surface can be cleaned with the compressed air from the spraying unit, then rinsed and wetted with running water. This job must be done immediately before spraying to prevent an insulating layer of dust forming immediately afterwards. The same applies if the sprayed concrete is built up layer by layer. If there is high water penetration, presealing or discharge of the water through drainage channels is necessary.

5.3 Spraying

Sprayed concrete and mortar are applied in layers, either in the same operation by repeatedly spraying over the same area or in a subsequent operation after a stop. After a long stop the surface must be cleaned and wetted again. The amount that can be applied in one operation depends on various factors:

- adhesive strength of the sprayed concrete mix (cement/max. particle size/accelerator)
- nature of substrate or base layer
- spraying process and settings
- spray output setting
- spraying direction (upward/horizontally)
- obstructions (reinforcement/water)

A different approach is required for different spraying directions.

When spraying downward, layers of any thickness can be applied. Make sure that the rebound is either embedded or disposed of so it does not remain on the surface.

When spraying horizontally, the thickness can be built up gradually in thin layers or for very thick applications the full thickness can be applied from below slope upwards in layers. Here again the rebound must be removed at the bottom before applying the next layer.

Fig. 26:
nozzle man spraying manually

Fig. 27:
automatic spraying head in operation

When spraying overhead, the material weight and adhesion of the sprayed concrete counteract each other, so that thinner layers have to be built up. As a general rule, a lower spray output and thinner layers generate less rebound, giving a better result in the end. Rebound is no problem here.

The sprayed concrete must be applied at right angles to the substrate or blinding concrete. This maximises adhesion and compaction and minimises rebound. The sprayed concrete or mortar is applied manually or mechanically in circular movements evenly over the whole surface. Spraying onto reinforcement is particularly difficult and requires experience because cavities due to spray shadows are very frequent. This problem is avoided by using steel-fibre-reinforced sprayed concrete.

The optimum distance for spraying is 1.2 to 1.5 metres, but is often within the 1 to 2 metre range. At greater distances the rebound and dust generation increase and the application efficiency is reduced.

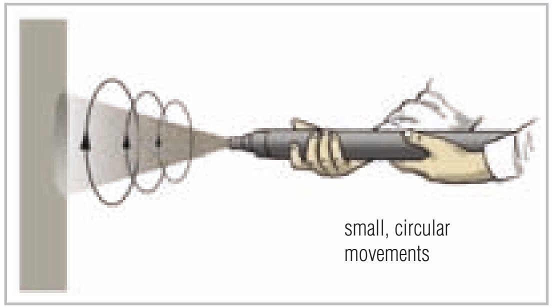


Fig. 28:
handling the spray nozzle for an even shotcrete surface

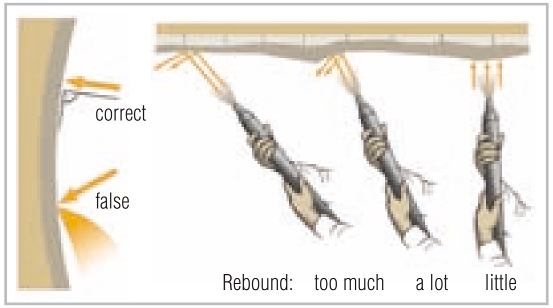


Fig. 29:
the influence of the spray angle on the rebound

5.4 Nozzle configurations

The nozzle configuration means the way in which the elements required for the application are fed into the main sprayed concrete jet. The following elements are fed into the various processes just before application:

Wet sprayed concrete dense-flow process	Wet sprayed concrete thin-flow process	Dry sprayed concrete thin-flow process
• Air (carrier medium) • Sprayed concrete accelerator	• Sprayed concrete accelerator (air as carrier medium)	• Water (carrier medium) • Sprayed concrete accelerator

The nozzle configuration depends on the process and choice of accelerators. Alkaline accelerators are preferably added 2 – 5 m behind the nozzle. Because they require a certain reaction time, better results are obtained in the early strength range. Due to the discontinuity in the jet caused by the duplex pump, alkaline accelerators release caustic water spray mist and aerosols into the supplying tunnel air. Correct feed 2 – 5 m behind the nozzle compensates for the pulsation and binds the accelerator. This greatly reduces the dust. The problems with caustic water vapour and aerosols are eliminated by using alkali-free accelerators. They are also extremely reactive and must be added just in front of the nozzle. The resultant short jet time of the sprayed concrete reduces the amount of dust.

The nozzle concentrates the jet and is responsible for the spray configuration. High-quality nozzles are designed to take all the conglomerate to the substrate without losses. At the same time all the particles must be distributed evenly over the cross-section of the jet.

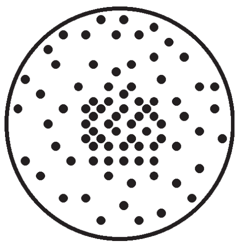


Fig. 30: poor distribution of the particles over the cross-section of the jet

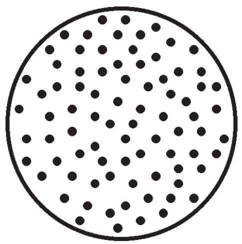


Fig. 31: good distribution of the particles over the cross-section of the jet

5. Sprayed concrete application

The spraying nozzle is one of the most important elements of the spraying system and represents the main wearing part in the concrete spraying process. The thorough mixing of air, concrete and setting accelerator takes place inside the nozzle.
Different advantages result from the new nozzle concepts we have developed. Reduction of the outlet opening allowed to optimize air consumption and at the same time to satisfy health protection regulations which must be observed ever more strictly. A further advantage is that in case of blockage the nozzle is expelled from the injector, thus preventing clogging of the openings through which air and accelerator are fed into the stream of concrete. The detached nozzle can be cleaned and easily mounted again. In order to keep the costs of the main wearing part low, the nozzles are manufactured with a minimum of material by means of a simple manufacturing process.

Bild 32: new spraying nozzle concept

Bild 33: traditional nozzle system

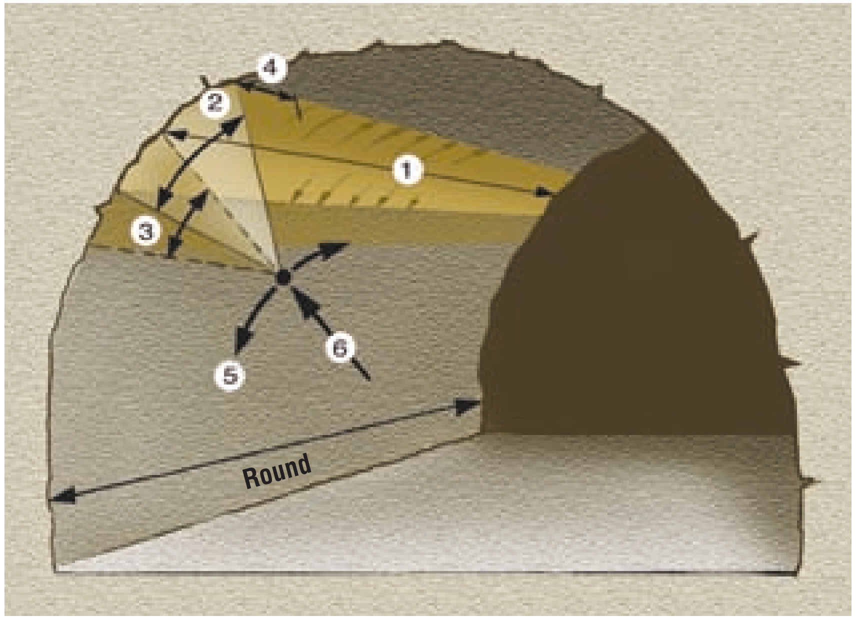


Fig. 34: diagram of nozzle manipulation

Explanation of above diagram:
1) Telescopic arm movement: l = length of round
2) / 4) Automatic nozzle movement: 2) pitch +/- 15 ° 2) / 4) = circular movement
3) Stiffening angle nozzle
4) Longitudinal angle nozzle
5) Surface contours tangential = rotary swivel vertical or horizontal
6) Cross-section alignment height

5. Sprayed concrete application

5.5 Early strength testing

Three methods are used to measure the strength development of sprayed concrete. They enable the development of mechanical resistance to be evaluated by practical means.

Strength development stage	Test method	Range of application
Very early strength	Needle penetration method	0 to ca. 1 N/mm²
Early strength	Bolt firing method	ca. 1 to ca. 15 N/mm²
Strength	Core compressive strength	over ca. 10 N/mm²

Very early strength

This method measures the force required to press a steel needle with defined dimensions into the sprayed concrete. The strength can be deduced from this resistance. This method is suitable for strength levels immediately after application of up to 1 N/mm².

Early strength development

With this method (Dr. Kusterle's bolt firing method), standardised nails are fired into the sprayed concrete with a Hilti DX 450L gun. The depth of penetration and pull-out force are

Fig. 35: very early strength from 0 to 1 N/mm² with needle penetration method

Fig. 36: very early strength from 1 to 15 N/mm² with bolt firing method

determined to obtain the compressive strength. The change in strength can be allowed for by using different nails and ammunition. This method has been simplified by Dr. G. Bracher so that the strength can be determined directly from the depth of penetration.

Strength development

Over about 10 N/mm², the compressive strength can be obtained by taking cores directly under a compression tester. This method is used mainly to check the required final strength after 28 days.

Fig. 37: core compression testing

5.6 Rebound

Reducing the rebound during the spraying process is one of the most complex challenges in the sprayed concrete process. The influences are so diverse that systematic control is extremely difficult. The most important factor is certainly the nozzle man. His technical skill and experience influence the rebound quantity enormously. This is of great economic and logistic importance because every tonne of rebound means twice the amount of work!

Factors influencing the rebound quantity:

- jet operator's technical skill and **experience**
- spraying direction (up, down, horizontally)
- spraying unit (air pressure, nozzle, spray output)
- spraying process (dry/wet sprayed concrete)
- sprayed concrete formulation (aggregate, grading curve, accelerator, fibre, binder)
- sprayed concrete (very early strength, adhesive strength, layer thickness)
- substrate condition (evenness, adhesion)

Fig. 38: sprayed concrete test for controlling rebound

The rebound changes during the spraying process. In the first few minutes it is mainly the larger aggregates that rebound because a fine adherend surface layer has first to be built up on the substrate, then, all the components in the mix rebound, during the spraying operation. The rebound quantity can be well controlled through the adhesive strength of the sprayed concrete.

Rebound quantity
Without separate measurements of the rebound under the conditions prevailing on site, the quantity can only be roughly estimated:

- rebound with dry sprayed concrete 20 % to 30 % for application vertically upward
- rebound with wet sprayed concrete 5 % to 15 % for application vertically upward

Reuse/disposal
In principle, sprayed concrete rebound is recyclable concrete with all the components of the original mix. However, it may still be contaminated (polluted) by the conditions prevailing on site. As with structural concrete, a small proportion of 10 % to 20 % max. of correctly treated sprayed concrete rebound can be reused without any problem.

5.7 Dust development

Dust occurs with any type of sprayed concrete application, but the dust quantities and types differ very considerably. There is a major problem with dry sprayed concrete because the components have a natural tendency to generate dust. The amount of dust generated can be reduced by suitable means. Measures to reduce the amount of dust for dry process sprayed concrete are:

- use of slightly moist aggregates (instead of air dried)
- sealing the conveyor feeding system
- correctly-adjusted and coordinated (synchronised) parameters at the nozzle (air (minimisation), water, accelerator (minimisation))
- low-pulsation material conveyance
- use of alkali-free setting accelerators
- use of spray manipulators for outputs > 6 m^3/h
- sprayed concrete admixtures to fix the deposited dust

Despite all these measures, two to four times more dust is generated by dry sprayed concrete than by the wet method. To further improve safety, only alkali-free setting accelerators should be used.

5.8 Spray shadows

Voids in the applied material, such as behind reinforcement, are a major problem in concrete repairs with sprayed mortar and also represent a challenge in conventional sprayed concrete construction. An experienced nozzle man can only minimise spray shadows by the right choice of spraying sequence. The importance of the nozzle man as the main criterion for high-quality sprayed concrete is essential.

5.9 Mechanisation/automation

Any operation or step that is constantly repeated demands improved automation. Nearly 100 years ago, the quick-setting mortar Sika®-1 was forced by hand between the joints of the rubble masonry walls by innumerable tunnel workers, whereas nowadays large quantities of high-quality sprayed concrete and mortar improved with additives can be placed rapidly on an industrial scale by a few specialists with high-performance spraying machines and concrete spraying systems. Mechanisation is well advanced in sprayed concrete technology and encompasses nearly every operation from production to application. The future lies in further automation of operations in the coming years, mainly to ease the burden on the jet operator. The aim must be to focus the experience of the operator on the sprayed concrete work and relieve him of the various mechanical sequences that can be automated. To be suitable for tunnelling, all new developments must be sturdy and extremely robust in design and be as simple in form as possible to have any chance of survival.

6. Spraying processes

The spraying process defines the conveyance of the sprayed concrete or mortar from its transfer from the delivery vehicle through to the nozzle and spraying of the material. We have seen that there is a distinction between dry and wet sprayed concrete. This distinction also applies to the processes, because they have to be conveyed and sprayed differently due to their material properties.

Sprayed concrete type	Method of delivery	Nozzle
Dry-sprayed concrete Dry-sprayed mortar Gunite	Thin-flow process	Added at the nozzle or immediately before: Water Setting accelerator
Wet-sprayed concrete Wet-sprayed mortar	Dense-flow process	Added at the nozzle or immediately before: Compressed air Setting accelerator
	Thin-flow process	Added at the nozzle or immediately before: Compressed air Setting accelerator

Summary of sprayed concrete processes

The two processes have specific advantages and disadvantages, resulting in their respective uses. These system-based characteristics are compared in general terms in the table below.

	dry	wet
dust formation	high	low
rebound	high	low
spray output	low	high
equipment costs	low	high
	low volumes ↓ small cross sections	high volumes ↓ large cross sections

Major criteria for selecting spray technique

6.1 Wet spraying process

Delivery by the dense-flow process is standard and very common for wet sprayed concrete, but this material can also be delivered by the thin-flow process using suitable machines. For so-called pumped concrete by the dense-flow process, the sprayed concrete is supplied by

- duplex pumps or
- helical pumps or
- squeeze pump (rotor pump)

Delivery by duplex pumps is the commonest method for dense-flow sprayed concrete. The material is loaded into the conveyor unit from a feed hopper and is conveyed through

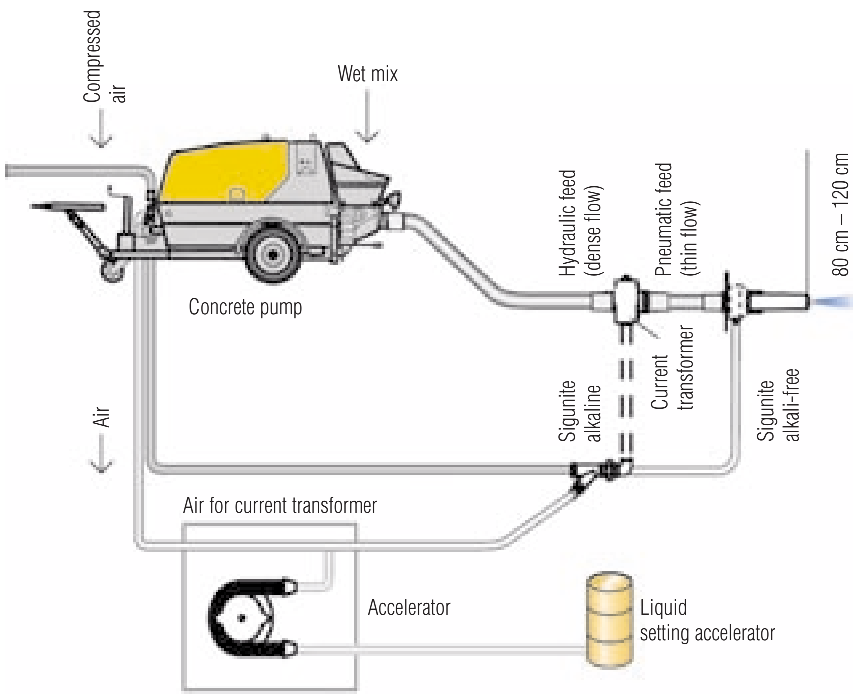


Fig. 39: dense-flow process for wet sprayed concrete

pipes and hoses. The main difference from conventional pumped concrete lies in the requirement for the pulsation to be as low as possible during conveyance to obtain a constant spray at the nozzle. Various ways of improving the rate of feed and reducing interruptions are used to achieve this.

The compressed air is fed via an air compressor in separate hoses to the nozzle. The metering unit feeds the accelerator to the nozzle, also in separate hoses. The dosage is synchronised with the concrete quantity so that the preset quantity of setting accelerator is always added.

Specially-designed rotor machines are required for delivery of wet sprayed concrete by the thin-flow process.

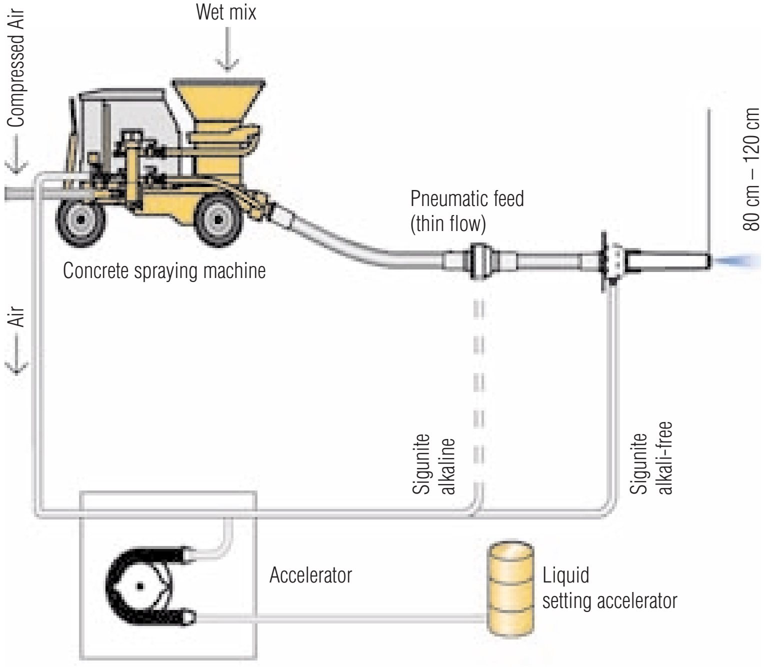


Fig. 40: thin-flow process for wet sprayed concrete

6. Spraying processes

6.1.1 Advantages

The advantages of the wet spraying process are many and varied. Wet spraying is the more modern and efficient method of installing sprayed concrete.

- higher spray output capacity, up to 25 m^3/h in some cases
- rebound quantity reduced by a factor of two to four
- great improvement in working conditions due to reduced dust generation
- reduced wear costs on the spraying equipment
- lower air consumption when spraying by the dense-flow process
- improved quality of the installed sprayed concrete (constant water content)

Wet sprayed concrete by the dense-flow process demands more work at the beginning (start-up) and end (cleaning) of spraying than the dry process. Also, the working time is preset during production and the sprayed concrete must be applied within that time, otherwise some concrete is wasted.

The ideal uses for the wet sprayed concrete process are based on the process advantages:

- high to very high spray outputs
- high and very high mechanical set concrete specifications
- high durability requirements

6.1.2 Machines

Manual and mechanical methods are used for the wet spraying process, but wet sprayed concrete is traditionally applied by machine. The high spray outputs and large cross-sections require the work to be mechanised. Concrete spraying systems with duplex pumps are mainly used for working with wet mixes. Unlike conventional concrete pumps, these systems have to meet the additional requirement of delivering a concrete flow that is as constant as possible, and therefore continuous, to guarantee homogeneous spray application.

Functional description of Putzmeister, double-piston pumps

The concrete pumps are hydraulically operated by electric or diesel motors by means of oil pumps. The delivery plungers are hydraulically linked through drive cylinders. They operate by push-pull. The reverse plunger generates a vacuum which is balanced by the material flowing into the cylinder. At the same time, the forward plunger forces the material in the cylinder (sprayed concrete) into the delivery pipe. At the end of the lift the pump reverses. The pipe switch pivots in front of the other full cylinder and the plungers reverse their direction of movement.

A core pump consists of hydraulic drive cylinder, delivery cylinder with delivery plunger, water tank between the two, concrete hopper with agitator, pipe switch, lever and reversing cylinder for the pipe switch.

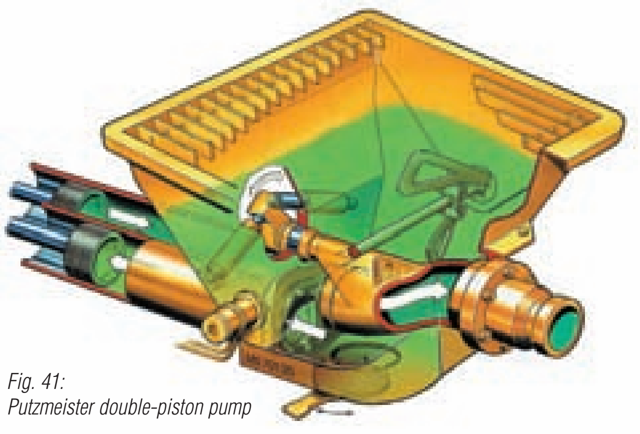


Fig. 41:
Putzmeister double-piston pump

6. Spraying processes

Bild 42: Sika®-PM702 E

Bild 43: Sika®-PM407 P

Bild 44: Sika®-PM622 PCD

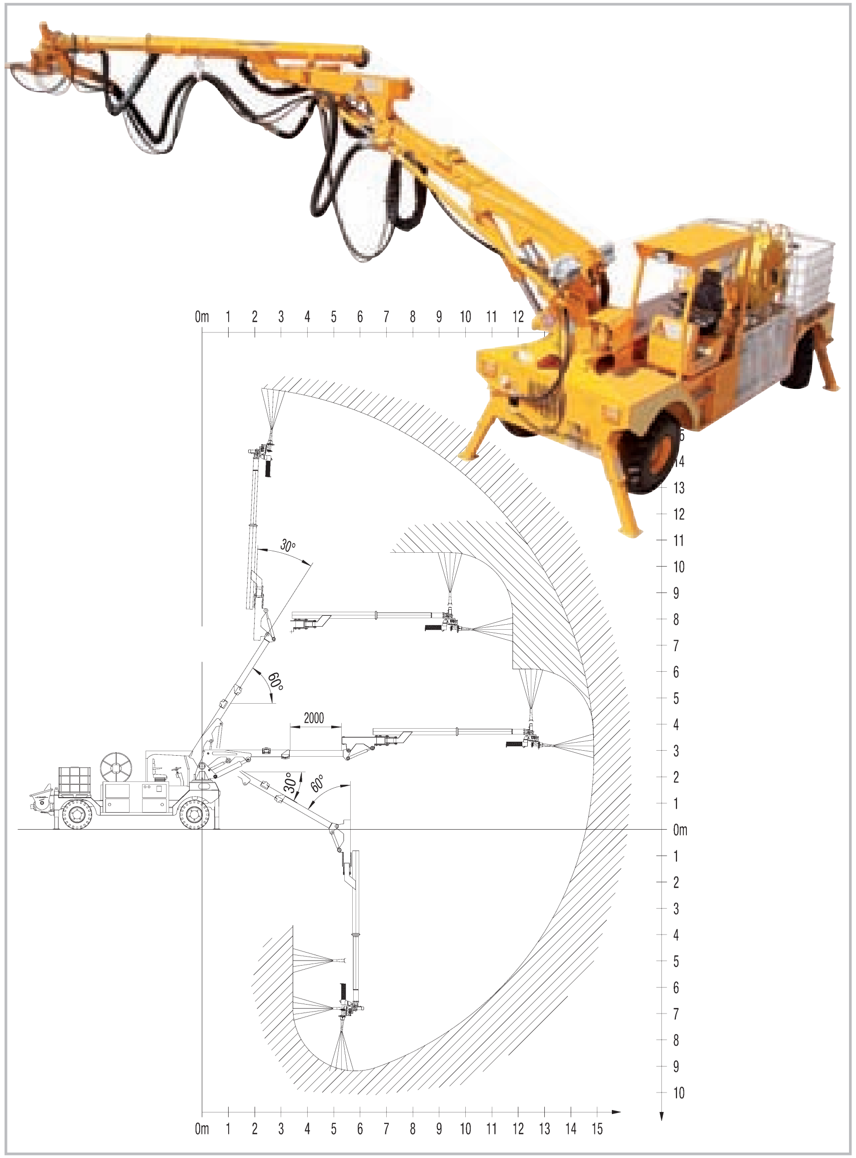


Fig. 45: Sika®-PM 500 with range diagram

6. Spraying processes

Like the sprayed concrete application methods, the entire tunnelling process is being further mechanised and automated. Tunnel boring machines (TBM) are taking the lead. Sprayed concrete is also used in TBM driving, if the substrate conditions and the relevant lining and stabilisation method allow. Sprayed concrete systems must be adapted to the conditions and requirements. They are mounted directly on the tunnel boring machines and are therefore an integral part of the mechanized tunnelling system with all its constraints and potential.

Fig. 46: Round arch spraying robot on the tunnel boring machine of the JV TAT, Gotthard base tunnel, section Bodio

Fig. 47: Spraying robot with telescoping boom on the tunnel boring machine Karahnjukar in Iceland

6.1.3 Dosing units

Special metering units are used to add the accelerator. To guarantee a consistent set concrete quality of the sprayed concrete, the dosing quantity regulation must correlate with the concrete quantity, in other words the metering unit must be synchronised with the concrete delivery. The metering unit must also be capable of covering the whole dosing range of the products used. (Minimum and maximum dosage multiplied by the cement content of the sprayed concrete quantity delivered.)

Functional description of ALIVA, metering units for setting accelerators
The liquid setting accelerator is fed in through a suction hose and enters the pump. A special hose is compressed by two rollers on a rotor and the content of the hose is conveyed by the revolution of the rotor. At the pump outlet the additive is fed to the valve and mixed with water or air (if required). An integral pressure switch prevents the pump and pipes being overloaded if there is a blockage in the line.
For minor applications the accelerators can be added by hand in powder form, but this is not controlled metering and is not viable for larger applications.

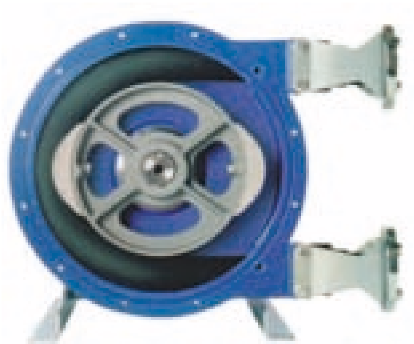


Fig. 48: schematic cross-section of squeeze pump

Fig. 49: Aliva®-403.5 Extended

6.2 Dry spraying process

Delivery by the thin-flow process is used for dry sprayed concrete. The sprayed concrete is conveyed by compressed air using

- rotor machines or
- compression chamber machines or
- helical machines

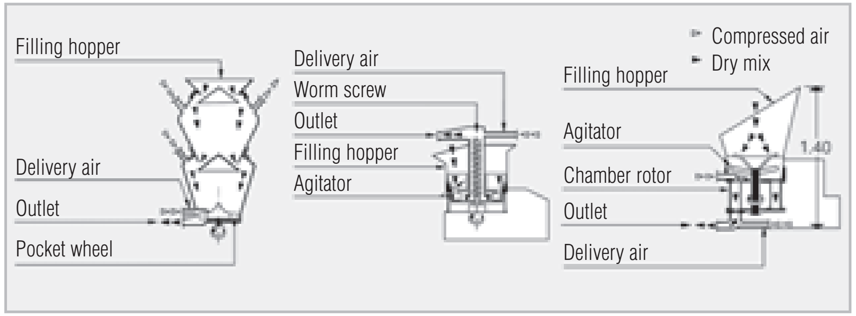


Fig. 50: operating principles of the two-chamber type machine, the screw-type machine and the rotor-typ machine

Delivery by rotor machines is the most frequent method of thin-flow conveyance for sprayed concrete. The material passes through a feed hopper into cylinder chambers of a structure similar to a revolver cylinder. The dry material is blown out in portions by compressed air and conveyed at high speed through hoses or tubes.

The setting accelerator is fed by the metering unit through separate hoses to the nozzle. The dosage is synchronised with the concrete quantity so that the set quantity of setting accelerator is always added. In the dry spraying process, accelerators can be replaced by special rapid cements that set in a very short time after wetting with water.

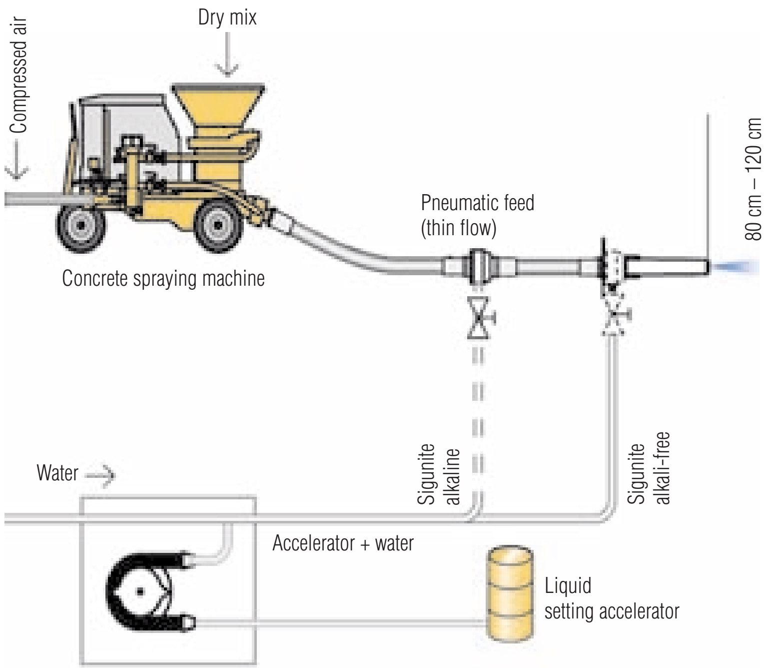


Fig. 51: thin-flow process for dry sprayed concrete

6.2.1 Advantages

The advantages of dry sprayed concrete lie in its flexibility. It is the traditional method of applying sprayed concrete, better known throughout the world.

- maximum very early strength for preliminary sealing or stabilising
- almost unlimited holding time (availability) of silo material
- no concrete waste

With dry sprayed concrete, the economics are affected by the high rebound quantities and dust generation and the higher wear costs.

The ideal applications for dry sprayed concrete and ready-mixed gunites result from the advantages of the process:

- concrete repairs
- preliminary sealing in high water penetration
- minor spraying works
- logistics concept not time dependent (site storage)

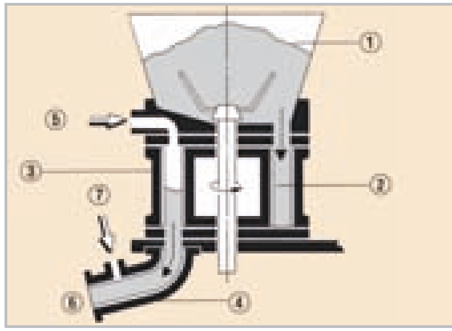
6.2.2 Machines

Both manual and mechanical spraying are used for the dry process. Because dry sprayed concrete is used very often but for lower spray outputs, manual application by a nozzle man is far more important than for wet sprayed concrete. As described, dry mixes are generally applied by rotor machines, which differ in a direct comparison in:

- spray output (m^3/h)
- uses (dry/wet/both)
- drive power (pneumatic/electric)
- size of spraying unit (dimensions/weight/convenience)
- control (manual/partly automated)
- operation (on the unit/remote control)
- additional installations (metering units/cleaning equipment)

Rotor machines are robust in design and have a long tradition, but there is still scope for development, concentrating on the following areas:

- increasing the resistance of wearing parts
- improving the dust protection
- more efficient chamber filling
- increasing the spray output in some markets



Functional description of Aliva®, rotor machines

The material passes through a feed hopper (1) into the rotor chambers (2). When the rotor revolves (3), the material moves through the blow-off chamber (4). The material is discharged from the rotor chamber through the top blow (5). The material is driven forward along with the bottom blow (7). It floats in a compressed air current (thin-flow delivery) in the delivery line at high speed to the nozzle.

Fig. 52: schematic cross-section of Aliva® rotor machine

Fig. 53: Aliva®-263 Extended by metering unit

Fig. 54: Aliva®-246.5 Basic

7. Sika Putzmeister product range

Concrete spraying systems

Sika®-PM500 P
Sika®-PM500 PC
Sprayed concrete systems with
BSA 1005 pump for wet sprayed concrete

Sika®-PM500 R
Sika®-PM500 RC
Sprayed concrete systems with **Aliva®-285** rotor for wet and dry sprayed concrete

Sika®-PM407 R
Sprayed concrete system with **Aliva®-285** rotor for wet and dry sprayed concrete

Sika®-PM407 P
Sprayed concrete systems with **BSA 702** pump for wet sprayed concrete

Sprayed concrete machines

Rotor machines for dry sprayed concrete
Aliva®-246
Aliva®-252

Rotor machines for dry and wet sprayed concrete
Aliva®-263
Aliva®-285

Concrete admixtures for sprayed concrete

Sika® ViscoCrete®
SikaTard®
Sigunit®
Sikament®
SikaFume®
SikaCrete®
SikaPump®
Sika Stabilizer®

Other products for sprayed concrete construction

FlexoDrain®

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