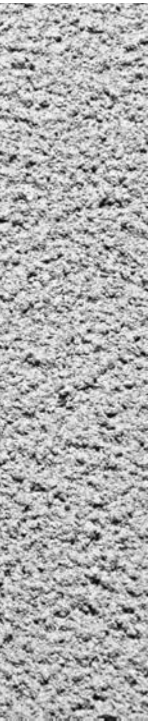

Sika Sprayed Concrete Handbook

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Editors
Sika Services AG
Tüffenwies 16
CH-8048 Zürich
www.sika.com

Putzmeister AG
Max-Eyth-Strasse 10
D-72631 Aichtal
www.putzmeister.de

Authors
Dipl.-Ing. Jürgen Höfler, Putzmeister AG
Dipl.-Ing. HTL Jürg Schlumpf, Sika Services AG
Dipl.-Ing. FH Markus Jahn, Sika Services AG

Layout
Sika Services AG
Corporate Marketing Service

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Putzmeister Sika
EXPERTS ON SPRAYED CONCRETE

Foreword

Sprayed concrete is a fast hardening material for stabilization and support of structures and for concrete applications without using any moulds. Sprayed concrete is an interaction of man, machine and concrete. Man, personified in the work of the nozzleman, requires technical skills 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 trend. This method is economically outstanding and almost unlimited technically, making it the obvious answer to a lot of challenges.

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

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.

The new edition (August 2011) was revised and supplemented by Markus Jahn. He works for several years as Corporate Product Engineer for Sprayed Concrete at Sika Services AG.

August 2011

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1. Table of Contents

2. Introduction

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

- shotcrete as material
- shotcreting as placing process
- shotcrete as construction method

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, 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. 2-1: Concrete spraying with Sika®-PM 500

2. Introduction

There are now two different sprayed concrete processes:

- **dry spraying**
- **wet spraying**

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 and dust

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 shotcrete 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 shotcrete 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 stabilization 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

2. Introduction

- totally flexible configuration of the layer thickness on site
- concreting without formwork
- reinforced sprayed concrete is also possible (mesh/fiber 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 mechanization and specialist workers are essential.

Fig. 2-2:
Dry spraying

Fig. 2-3:
Wet spraying

3. Uses 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, tunneling and special underground construction, in fact throughout the construction industry. The following uses are widespread:

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

In terms of importance, tunneling, mining and concrete repairs head the list. In tunneling and mining, the main uses are for excavation stabilization, 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. 3-1: Excavation stabilization with shotcrete

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 stabilization. Whether tunneling 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 stabilization and lining. Predetermined deformation of the excavated section is often allowed and only then is the stabilization given a non-positive seal. This causes the stresses to be distributed around the excavation section and in the area around the excavation face.

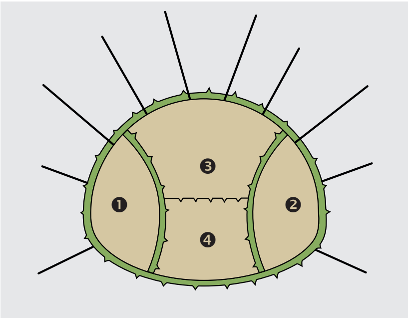


Fig. 3-2: Side wall method: side galleries (1+2), crown (3), core (4)

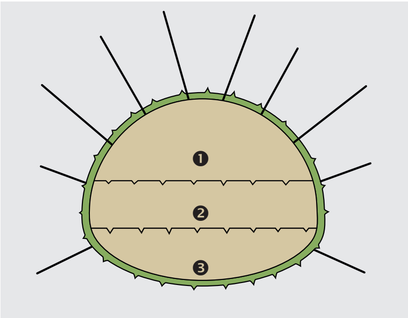


Fig. 3-3: Driving of crown method: top heading (1), bench (2), invert (3)

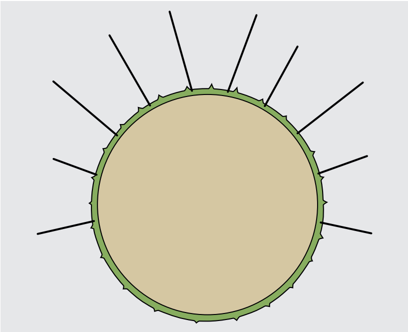


Fig. 3-4: Hard rock TBM method & full-face drill and blast method

3.2 Stabilization

Sprayed concrete is the perfect material for excavation stabilization. Its unique flexibility in the choice of application thickness, material formulation (fiber), 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 stabilization.

A distinction is made between full excavation and partial excavation according to the load-bearing properties and stability of the substrate. Excavation is done by drill and blast or mechanical methods. In line with the old saying about tunneling: "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 stabilization 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 (fiber/steel reinforcement). By using steel rings and mesh, sprayed concrete becomes the lattice material between the beams. By using bolts, the load-bearing properties

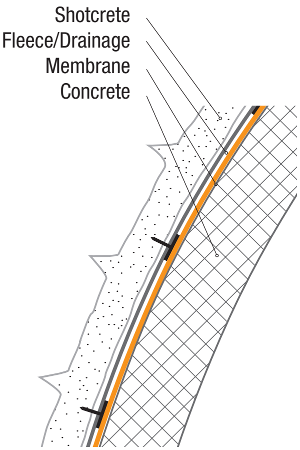


Fig. 3-5: Tunnel lining with shotcrete, membranes, concrete

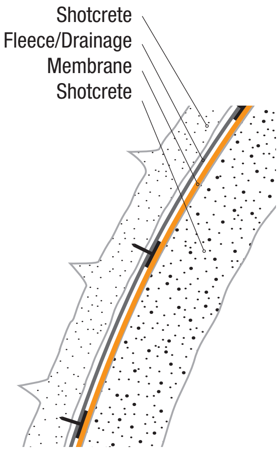


Fig. 3-6: Tunnel lining with shotcrete, membranes, shotcrete

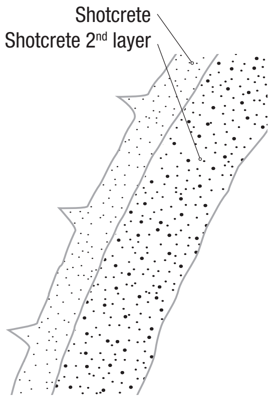


Fig. 3-7: Tunnel lining with shotcrete

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 Tunneling Method (NATM), the German Core Method and the Belgian Underpinning Method. The full section is divided into smaller sections which are each temporarily stabilized and are only joined to form the full section at the end. In the full excavation application, partially and fully mechanized 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. 3-8: Side wall method

Fig. 3-9: Driving of crown method

3.3 Lining

The final lining of a tunnel is the permanently visible reference of the tunneling contractor. The exception is a final lining with paneling. Inner lining 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.

Fig. 3-10: Lining with sprayed concrete

Accessibility is usually difficult, which means that so-called form vibrators are used, although they have a limited depth effect and are therefore very labor-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 high requirements in evenness, sprayed concrete is also suitable for the final lining. Before installation of the waterproofing membrane, the sprayed concrete surface is often leveled as smoothly as possible with a finer shotcrete (gunite), which greatly improves the conditions for laying the waterproofing membranes without wrinkles.

Table 3-1: Comparison of lining methods (shotcrete versus concrete)

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 stabilization: - Saving one full operation
Inner lining concrete	Even concrete surface: - less air resistant (ventilation) - better lighting conditions - more attractive appearance - simpler fixing of installations Avoiding of concrete inhomogeneities due to omitting of spraying process Without the “very early strength“ requirement, more options in the concrete mix for durability requirements

4. Sprayed Concrete Materials

4.1 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 more than one parameter at the same time during the testing phase. Only the technically correct and economically viable solution will satisfy everyone.

4.1.1 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 lime 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, give good bonding capability and 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 stabilization.

The cement content is in general 300 - 450 kg/m³. It is depending on the spraying process and the shotcrete requirements.

4.1.2 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 stabilization)
- to reduce the pump pressure during delivery (lubricant)
- to substitute parts of cement (cost optimization)
- to accelerate (high early strength)

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

Table 4-1: Effects of additives in sprayed concrete and mortar

Effect	Additive Types	Remarks
Hydraulic	Cement	Cement-type and -quantity influence the workability and strength development
Latent hydraulic	GGBS (Slag) Fly ash (type W)	Slow down the strength development and increase the durability
Pozzolanic	Silica fume Fly ash (type V)	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 filler (e.g. limestone filler)	Do not themselves develop strength but help by improving the particle matrix

Silica Fume

Silica fume is amorphous SiO_2, 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. Silica fume 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.

Table 4-2: Characteristics of additives in sprayed concrete and mortar

Characteristic	Cement	Silica Fume	Fly Ash	Slag	Stone Filler
Fresh concrete					
Handling	++	++	+++	+	+++
Water retention capacity	++	+++	+	+	++
Strength development					
Very early strength up to 4 h	+++	+	–	–	+ / –
Early strength up to 12 h	++	++	–	–	+ / –
Final strength	++	+++	++	+++	+ / –
Durability					
Water penetration resistance	++	+++	++	++	+
Sulphate resistance	–	++	+ / –	+++	+ / –
ASR resistance	–	+ / –	+ / –	+++	+ / –

+ improving – deteriorating

4.1.3 Aggregates

The aggregates (stone particles) form the framework of the sprayed concrete matrix. Approximately 75 % of the concrete 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 ≤ 0.125 mm 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 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.

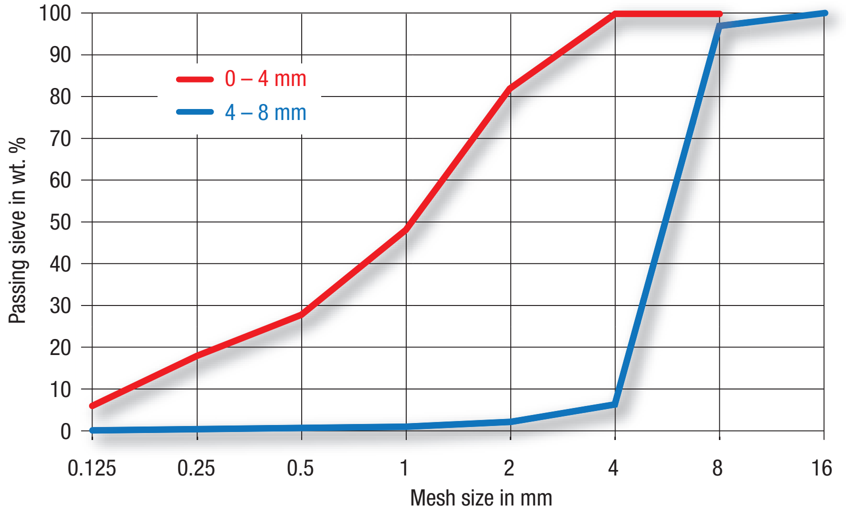


Fig. 4-1: Particle size distribution of individual components

4.1.4 Fines Content

The fines content consists of:

- the cement
- the 0 to 0.125 mm granulometric percentage of the aggregate
- and any concrete additive(s)

It acts as a lubricant in the fresh concrete to improve the workability and water retentivity. The risk of mixture separation during installation is reduced and compaction is made easier. However, fines contents which are too high produce doughy, tacky concrete. There can also be a greater shrinkage and creep tendency (higher water content).
The following quantities (green) have proved best:

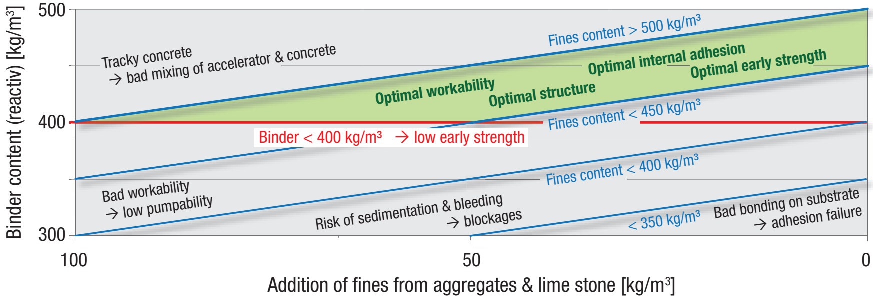


Fig. 4-2: Influence of fines content on shotcrete mix design (0–8 mm aggregates)

4.1.5 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
- sugar
- salt

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.

4.2 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. 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 or binder weight. They are added in an approximate range of 0.5 % to 7.0 %. This gives quantities of 2 kg/m³ to 32 kg/m³, 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 shotcrete accelerator, which is adding immediately before spraying.

Table 4-3: Target specifications for the use of sprayed concrete and mortar additives / admixtures

Sprayed Concrete Target Specifications	Control Parameters	Concrete Admixtures for Target Achievement
Compressive strength Flexural strength Durability	Set concrete characteristics	Water reducer Additives Fiber reinforcement Curing agents
Pumpability Sprayability Spraying configuration	Workability	Mix stabilizers Additives Water reducer
Strength development	Setting and hardening	Shotcrete accelerators Water reducer
Working time	Open time	Setting retarders Slump keeper

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

Fig. 4-3: Label of EFCA

4.2.1 **Setting and Hardening Accelerator for Shotcrete** (shotcrete accelerator)

Chemistry of Liquid Alkali Free Accelerators

Currently, liquid alkali free accelerators have become the standard in high demanding shotcrete applications, worldwide, i.e. due to their beneficial properties regarding applicability and environment, health and safety (EH&S). These products which are based on aqueous solutions or suspensions of aluminum sulphate compounds are easy to handle, i.e. with respect to a constant dosing and secure a very good development of the early strength combined with optimal shotcrete properties.

With respect to the term “alkali free” one has to distinguish between two chemical aspects and the product’s effect on the shotcrete properties resulting from these:

- Alkalinity (as synonym for basicity)
  The basicity or pH value of alkali free accelerators is low, usually about pH 3.0. This affects basically, the health and safety aspect during application since human tissue is much more endangered by high alkaline liquids than by weak acids. The pH of alkali free accelerators is in the range of weak acids, e.g. similar to that of soft drinks like fruit juices or Coke (pH 2.4 – 3.0).

- Alkali Ion Content
  The content of alkali ions, e.g. sodium and potassium, affects the concrete properties. With increasing alkali content the final strength of shotcrete is reduced as well as its durability.

Chemistry in Alkali Free Accelerated Shotcrete
There are certain highly demanding requirements on shotcrete due to its specific spraying application: Whereas for the fresh concrete a very good workability is required, i.e. slump life and pumpability, the properties of the sprayed concrete are totally inversed from this. An immediate strength has to be achieved which enables even over head application of reasonably thick concrete layers are strong enough to bear their own weight. Any retardation of the cement hydration might yield in a delayed collapse of the shotcrete construction due to other, secondary effects, e.g. creeping or water infiltration.

The most important properties of accelerated shotcrete, setting and early hardening, are achieved due to two main chemical reactions inducted by the alkali free accelerators (based on aluminum sulphates and aluminum hydroxisulphates). These reactions largely take place one after the other, however, there is still an overlap and a chemical interference between them:

- *Aluminate Reaction in Alkali Free Accelerated Shotcrete*
  Initially, starting with the accelerator mixed into the concrete right at the nozzle there is a very pronounced formation of ettringite. This immediately starting ettringite precipitation which takes place during a curing period of ca. one hour forms an initial solid matrix which is strong enough to enable save shotcrete application. However, due to chemical and technical reasons a maximal compressive strength as result from this primary shotcrete reaction usually does not exceed ca. 1.0 to 1.5 MPa.
  In view of detrimental factors on the young shotcrete, e.g. due to static forces (over head application) or water ingression, this initial strength gain has to be followed by a subsequently strengths gaining process, the silicate hydration as secondary shotcrete reaction.
- *Silicate Reaction in Alkali Free Accelerated Shotcrete*
  Even in fresh shotcrete quite often retarders are used to achieve a prolonged workability of the mix. However, once the shotcrete is applied the cement retardation, i.e. the retardation of the silicate hydration reaction becomes adversely with respect to the shotcrete performance. During the curing of young shotcrete the second effect of alkali free accelerators is the cancellation of the initial cement retardation (as required for the workability) which yields in an earlier onset of the silicate reaction compared to fresh concrete.

Other Liquid Accelerators

Apart from the above described current state of the art accelerator technology, using alkali free accelerators, there are elder types of liquid accelerators used in many countries, i.e. based on aqueous silicate or aluminate solutions. These accelerators are not alkali free, meaning they contain rather high amounts of alkali ions and they are basic liquids exhibiting a very high pH beyond pH 11.

The chemical interactions in shotcrete when using these accelerators differ from the above described for alkali free accelerators. Apart from these differences the use of non alkali free accelerators in shotcrete yields in negative effects regarding safety issues during application and regarding the shotcrete durability. Due to the high alkalinity (pH) these products bare the danger of burns for human tissue, i.e. for eyes. This holds either for direct contact (skin, eyes) as well as for aerosols of these accelerators which are rather harmful on respiration (lung). Even these accelerators usually yield in reasonable good early strength development, the final shotcrete properties are adversely affected, i.e. the final strength is strongly reduced and the concrete is easily leached from water infiltration. The latter effect generates further problems in case of draining systems as these are rapidly clogged by the leachate of the shotcrete. Durability in general is an issue as due to the large amounts of alkali ions introduced by the accelerator, the risk of alkali silicate reaction is enhanced for this shotcrete.

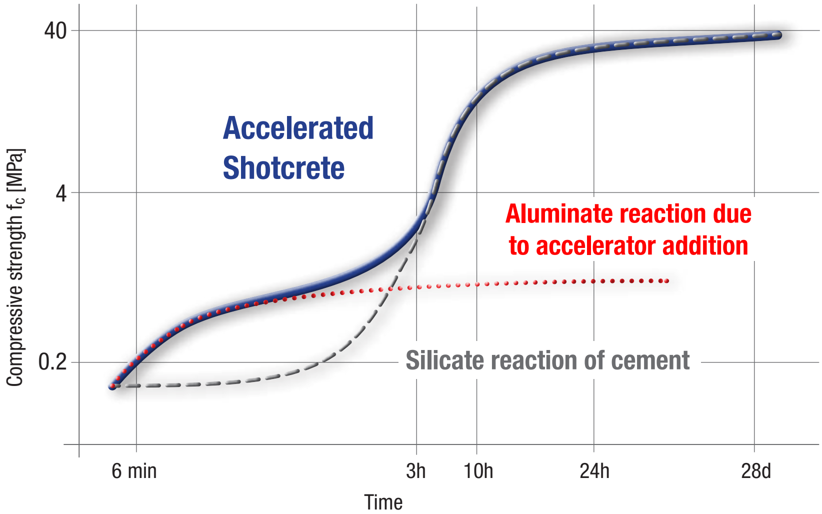


Fig. 4-4: Interacting of aluminate and silicate reaction

Table 4-4: Accelerator types and their main properties

Properties	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	– –	–	+++

+ improving *– deteriorating*

Table 4-5: Sigunit® types and their main uses

Type	Product	Use / Effect	Remarks
Liquid, alkali free shotcrete accelerator	*Sigunit®-L AF*	• Heading stabilization in tunneling • 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 • 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 shotcrete accelerator	*Sigunit®-AF*		
Liquid, alkaline shotcrete accelerator	*Sigunit®-L*	• Heading stabilization in tunneling • Rock and slope stabilization • Very high early strength • Lower rebound • Can be sprayed on a wet substrate	• For the dry or wet spraying process • Final strength reduction compared with the non-accelerated original concrete • Aggressive to human tissue
Powder, alkaline shotcrete accelerator	*Sigunit®*		

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

- *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, additives with a high alkaline content are not discharged into ground and drainage water.
- *Safe Handling:*
  Alkali free shotcrete accelerators are not a hazard during transport, storage, decanting or dosing.
- *Secure Concrete Quality:*
  The use of alkali free shotcrete accelerators minimizes the negative effect of the concrete hardening and improves the tightness of the sprayed concrete and therefore its durability.
- *Safe Disposal:*
  Alkali free shotcrete 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 basic if their pH value is between 7 and 14.

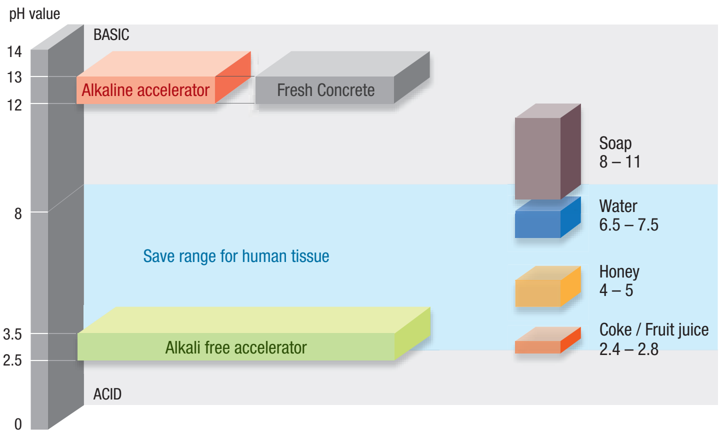


Fig. 4-5: pH range of shotcrete accelerators

4.2.2 High-range Water Reducers (HRWR)

Along with the shotcrete accelerator, the high-range water reducer (superplasticizer) is the most important concrete admixture in wet sprayed concrete. For shotcrete accelerators to be used effectively, the water content in the fresh concrete must be limited. The maximum w/b ratio is generally defined as 0.50, but a maximum w/b ratio below 0.48 is better for performance and quality.

Table 4-6: Calculation of water content

Water / Binder Ratio	Example I	Example II
Maximum value: 0.50	425 kg/m³ CEM I 42.5 → 212.5 liter/m³	300 kg/m³ CEM I 42.5 & 125 kg/m³ fly ash (k=0.4) → 175 liter/m³
Maximum value: 0.46	425 kg/m³ CEM I 42.5 → 195.5 liter/m³	300 kg/m³ CEM I 42.5 & 125 kg/m³ fly ash (k=0.4) → 161 liter/m³

In addition, the workability time and internal cohesion of the fresh concrete are influenced by the high-range water reducer, as therefore are its overall properties. The composition of the water reducer also impacts on the effect of the shotcrete accelerator. All of the properties referred to below are predominantly determined by the concrete formulation and these are influenced and controlled by the water reducer.

The main requirements for high-range water reducers in sprayed concrete can be summarized as follows:

Water Reduction
- Achieving the required flowability when the water content in the fresh concrete is greatly reduced. Ideal fresh concrete consistency: flow table spread 550 to 650 mm.

Workability Time
- The fresh concrete consistency must remain as constant as possible over the required workability time, because a soft consistency is specifically required for pumping

Pumpability
- A low viscosity (softness) promotes both good concrete pumpability and homogeneous mixing of the shotcrete accelerator (Sigunit) into the concrete in the stream transformer at the nozzle.

Compatibility

- The nature and effects of high-range water reducers, shotcrete accelerators and any other concrete admixtures used must all be compatible. Therefore these combinations must be pre-tested and approved by the admixture manufacturer and concrete producer. A random combination of different products and mixes can give very unsatisfactory results.

In terms of concrete technology, alternative high-range water reducer material technologies are differentiated according to their water reducing performance and suitability:

Water Reducer (WR)

- The limited water reduction capability (5 – 10 %), frequently together with their chemical composition, makes WR unsuitable for use in sprayed concrete.

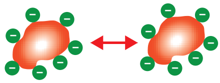
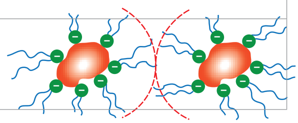
High-range Water Reducer (HRWR)

- There are two technologies available for HRWR which are:

  The Naphthalene (SNF) and Melamine (SMF) types, which are characterized by good water reduction and outstanding compatibility for combination with shotcrete accelerators. The options for extending workability times and their maximum water reduction are somewhat limited however.

  The new generation of Polycarboxylates (PCE) types is characterized by optimum water reducing performance and they allow almost any extended workability time. The interaction between this type of high-range water reducer and shotcrete accelerators is rather more complex and therefore these products must be specifically matched.

Table 4-7: Types of water reducer

Type of Water Reducer	**Chemical Base**	**Water Reduction Potential**	**Effect**
WR	Carbohydrate / Lignin sulfonate	5 – 10 %	Electro statical forces: 
HRWR	Naphthalene (SNF) & Melamine (SMF)	5 – 25 %	
	Polycarboxylate (PCE)	10 – 40 %	Steric repulsion: 

Characteristics and Advantages of Polycarboxylate Ether Technology (PCE)
The major characteristic of polycarboxylate ether-based superplasticizer technology is their targeted polymer design to achieve specific concrete properties.
The first component – backbone with carboxyl groups – is responsible for the attainable water reduction / initial slump and mixing time respectively. The second one – side chains – determines the slump keeping capability of the superplasticizer, affected by an increasing number of side chains. The crucial factor is the limited space for carboxyl groups and side chains along the backbone. Either a carboxyl group or side chain can be attached at a certain location. This leads to the technological limitation that there are essentially three different types of polymers – water reducing, slump controlling and slump retention polymers.

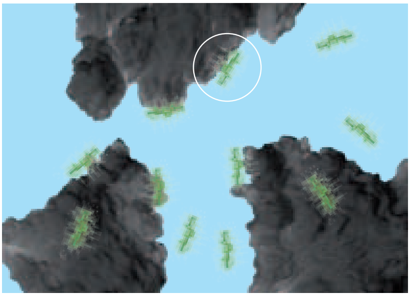


Fig. 4-6: Adsorption of the polymer (backbone) on the cement grain

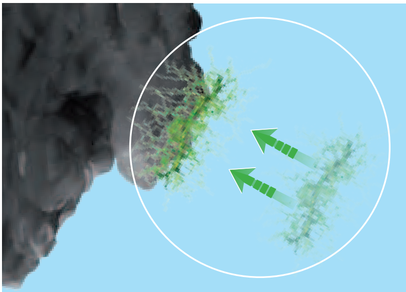


Fig. 4-7: Detail of the adsorption of the polymer (backbone) on the cement grain

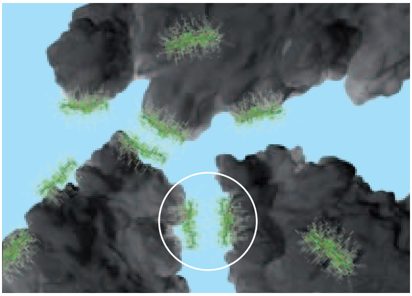


Fig. 4-8: Improved workability due to steric hindrance

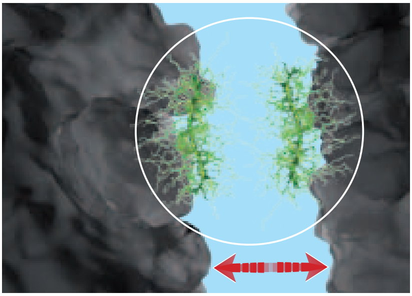


Fig. 4-9: Detail of improved workability due to steric hindrance

4.2.3 Consistency Stabilizers / Set Retarders

Sprayed concrete is most used in tunneling and mining, where major logistical challenges also exist and therefore (for example) the workability times of the concrete must be made as flexible as possible. This is effectively achieved by sprayed concrete because the start and rate of hydration can be controlled independently by the shotcrete accelerator added at the nozzle. As a result the workability can be extended over many hours and then the other logistical operations such as the concrete production, transport, waiting times, installation and breaks can also be adequately planned and controlled.

SikaTard®-930
Consistency stabilizers for shotcrete such as SikaTard®-930 enable almost any fresh concrete workability times to be selected. The specific time effect is also dependent on the batching, cement type, binder content, water content and temperature conditions.

Table 4-8: Extension of workability time by additional adding of SikaTard®-930

Required Workability Time	Product	Recommended Dosage on Cement
1 to 3 hours	*Sika® ViscoCrete®-SC*	Depending on required w/c-ratio: 0.8 – 1.5 %
4 hours	*Sika® ViscoCrete®-SC* *SikaTard®-930*	0.8 – 1.5 % 0.2 – 0.4 %
8 hours	*Sika® ViscoCrete®-SC* *SikaTard®-930*	0.8 – 1.5 % 0.4 – 0.6 %
12 hours	*Sika® ViscoCrete®-SC* *SikaTard®-930*	0.8 – 1.5 % 0.6 – 0.8 %

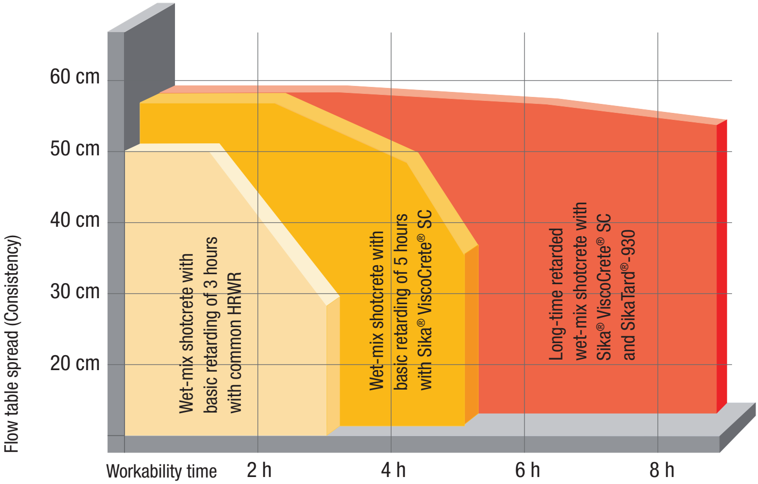


Fig. 4-10: Workability time of wet sprayed concrete mixes

4.2.4 Mix Stabilizers

Softness and pumpability are the two key criteria for evaluation of fresh concrete for sprayed concrete applications.

Softness
The softness of the concrete should not be confused with its flowability. Softness defines the viscosity of the fresh concrete. The softer the concrete, the more easily and completely it can be broken up in the stream transformer at the nozzle and the more homogeneously and therefore efficiently, the set accelerator can be injected and dispersed in it.

Flowability
The flowability also influences the filling capability for transport in containers or truck mixers, plus even more importantly, for the degree of filling that is possible in the cylinders of the concrete pumps in the intake phase and therefore the pumping efficiency.

Pumpability

The two properties (softness and flowability) together are essential for evaluation of the pumpability of concrete. Firstly for the delivery rate, then secondly for the pumping energy requirements.

To control the fresh concrete properties, special concrete admixtures can be added for control of the flowability, softness and pumpability, in addition to the right concrete formulation. The aim of all of these measures is always optimization of the mix stability.

Fines Content

A fines content ≤ 0.125 mm in kg/m³ and the volume of the fines content in L/m³ are determining factors. The minimum content required is dependent on the delivery method and distance, the maximum grain size and the type of aggregates (rounded or crushed).

Sika® Stabilizer

Stabilizers such as Sika® Stabilizer improve the internal cohesion of concrete mixes and produce a more stable and homogeneous mix. Stabilizers are mainly used when the fresh concrete tends to separate or segregate and this cannot be improved by further optimizing the existing mix design.

SikaPump®

As the name suggests, pumping agents such as SikaPump® are used to improve pumpability in the dense-flow wet spray process. As well as improving the mixes pumpability, they increase “lubrication” of the pipes and therefore improve also the continuity and reduce the energy and pressure required.

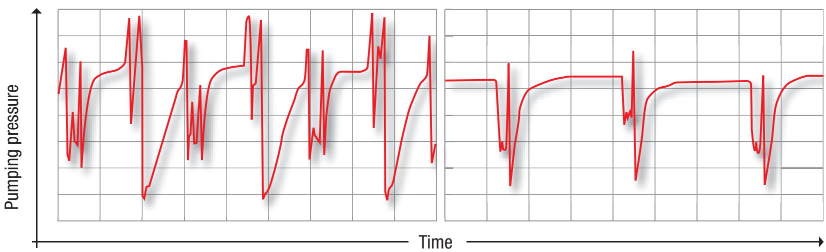


Fig. 4-11: Without SikaPump®: uncontinuous pumping pressure

Fig. 4-12: With SikaPump®: continuous pumping pressure

Table 4-9: Summary table of sprayed concrete admixtures

Type	Product	Use / Effect	Remarks
Accelerator	*Sigunit®*	Concrete placing without using any moulds	Addition at nozzle
Superplasticizer	*Sika®ViscoCrete® SC*	• 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	*SikaTard®*	• Adjustable workability • No cleaning of pumps and hoses necessary during the retarding phase	
Silica fume	*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 silica fume dries concrete out very quickly on the surface
Polymer-modified Silica fume	*Sikacrete®-PP1*	As for *SikaFume®* plus: • Significant water reduction • For very high quality	As for *SikaFume®*
Pumping agent and stabilizer	*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
Lubrication agent	*SikaPump®-Start 1*	• Reduces the friction resistance of hoses / pipes • Replaces cement slurry as pump start agent	Lubrication mix must not be sprayed onto application area

5. 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.

5.1 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 is a normal strength development required, comparable with that of structural concrete. The strength development is influenced by the same factors:

- aggregate type
- cement type and content
- water content
- temperatures in the concrete and the environment (substrate and ambient)
- 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 stabilization, 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.

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

5.2 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 used shotcrete accelerators and the skill of the nozzleman 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 fibers for sprayed concrete and mortar reinforcement is ideal for flexible forming of the material. Steel-fiber-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 ductility of the reinforced sprayed concrete.

Table 5-1: Final compressive strengths according to SN 531 198 (Switzerland)

Sprayed Concrete Class SC	Compressive Strength Class	Exposure Class	Recommended areas of application
SC 1	C16/20	X0	Filling of joint fissures and cavities
SC 2	C25/30	X0	Immediate support
SC 3	C25/30	XA1, XD1	Further layers of the temporary support; respectively, first layer, if there are no special requirements regarding immediate support
SC 4	C30/37	XA1, XD1	Temporary support for single-shell lining, reinforced
SC 5	C30/37	XA2, XD1	
SC 6	C30/37	XA1, XD1, XC3, XF3	Lining for single-shell lining, reinforced or unreinforced
SC 7	C35/45	XA1, XD3, XC3, XF4	

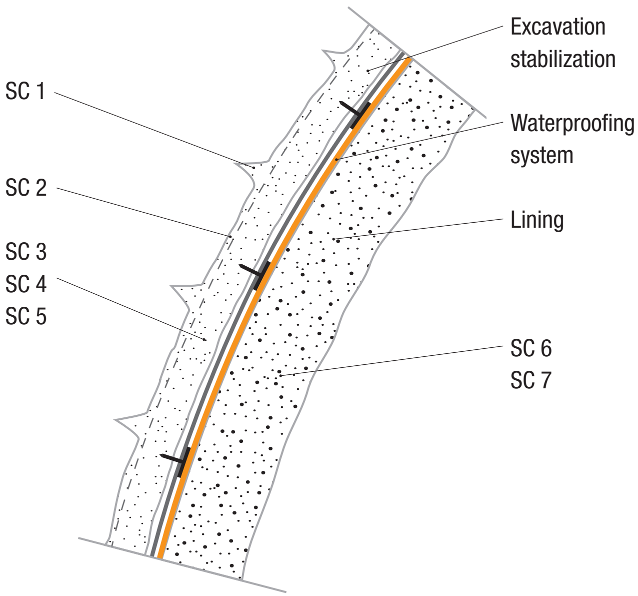


Figure 5-1: Sprayed concrete classes according to SN 531 198 (Switzerland)

5.3 Fiber-reinforced Sprayed Concrete

Fiber-reinforced sprayed concrete has now become much more important due to the development of new and more effective types of fiber, 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 labor 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 fiber-reinforced sprayed concrete. Its main advantages are:

Table 5-2: Fiber types and their properties

Properties \ Fiber Types	Micro-synthetic fibers Ø < 0.30 mm	Macro-synthetic fibers Ø > 0.30 mm	Steel fibers
Improves cohesion (bleeding)	x		
Reduces plastic settlement cracking	x		
Reduces plastic shrinkage cracking	x		
Increases impact & abrasion resistance	x		
Increases shatter / spalling resistance	x		
Reduces permeability	x		
Increases explosive spalling resistance (fire)	x		
Long-term crack control		x	x
Increased fatigue & impact resistance		x	x
Improved post crack ductility (energy absorption)		x	x

Fig. 5-2: Well distributed fibers in concrete

Fig. 5-3: Steel fibers for improving energy absorbtion of concrete

In principle, all fiber types and materials are suitable for sprayed concrete, where the material is used in tunneling, steel fiber is generally most appropriate. Carbon fiber has ideal properties but is completely uneconomic for use in conventional sprayed concrete. Glass fiber is only suitable for special fine-particle applications and has to meet special requirements for its long-term behaviour. Polymer fiber 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 fiber improves the fire resistance of concrete in general. Modern generations of plastic fibers are now appearing in the traditional steel fiber applications.

Steel fiber surpasses reinforcing bars and mesh on cost-performance in nearly every case.

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

- The fresh concrete consistency must be more plastic so that the fiber-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 silica fume.

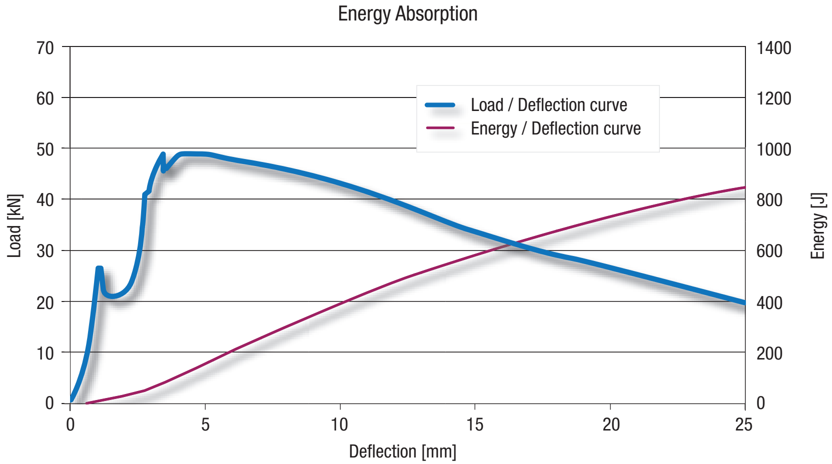


Fig. 5-4: Load / Deflection curve of steel fiber reinforced shotcrete, EN 14488-5

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

Table 5-3: Energy absorption classes according to EN 14487-1

Energy absorption class	Energy absorption in Joules [J] for deflection up to 25 mm	Application for following ground / rock conditions
E500	500	'sound'
E700	700	'medium'
E1000	1000	'difficult'

Fig. 5-5: Energy absorption testing of fiber reinforced sprayed concrete according to EN 14488-5

5.4 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 fiber (polypropylene), the temperature drop in a thin wearing course can be guaranteed; it has to be replaced after a fire.

Fig. 5-6: High temperatures destroy unprotected concrete

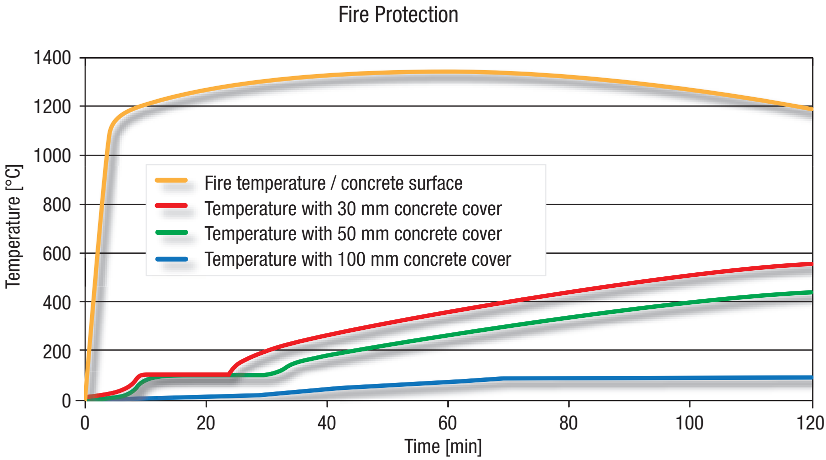


Fig. 5-7: Fire testing of fire resistant sprayed concrete

5.5 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 shotcrete accelerator or special cement. Traditional shotcrete 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 can be added to the sprayed concrete during production and when integrated perform the curing function.

Table 5-2: Measure to change sprayed concrete characteristics and to achieve high durability

Target Parameter	Measure	Product
To increase compressive strength	• Reduced water content • Use of silica fume	*Sika®ViscoCrete® SC* *SikaFume®*
To improve waterproofing	• Reduced water content • Use of silica fume	*Sika®ViscoCrete® SC* *SikaFume®*
To increase frost resistance	• Reduced water content • Use of silica fume	*Sika®ViscoCrete® SC* *SikaFume®*
To increase sulphate resistance	• Reduced water content • Use of sulphate resistant cement and/or silica fume • Minimized accelerator dosage	*Sika®ViscoCrete® SC* *SikaFume®* *Sigunit®-L AF*
To increase ASR resistance	• Reduced water content • Use of binder with low Na_2O equivalent • Use of aggregates with low ASR potential • Minimized accelerator dosage	*Sika®ViscoCrete® SC* *Sigunit®-L AF*

As with any human activity, the quality of the installed sprayed concrete is largely determined by people, in this case the nozzleman 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.

6. 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 shotcrete 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.

6.1 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 tunneling. 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

6.2 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.

6.3 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.

Table 6-1: Shotcrete components and their effects

Ingredients	**Type**	**Amount [kg/m³]**	**Effect**
Binder	Cement	400	It is the 'glue' of the concrete matrix High strength development Good pumpability Bonding on the substrate after spraying
Water	No contaminants	192	Hydration process Good pumpability
Aggregates	0 – 8 mm	1718	Granular structure of the concrete Due to the rebound the size of the aggregates are limited to 8 mm
Superplasticizer	*Sika® ViscoCrete® SC*	4	Reduces the water demand Increases the workability
Weight/m³		*2310*	
Accelerator	*Sigunit®-L AF*	24	Accelerates the strength development Concreting without formwork

Table 6-2: Mix design for wet sprayed concrete

Mix Design of 1 m³ Shotcrete	**Ratio**	**kg**	**kg/L**	**Liters**
Mix design				1000
Cement		400	3.15	127
Water	0.48	192	1.00	192
Air voids	4 %	0	0.00	40
Aggregates	100 %	1718	2.68	641
Sand 0 - 4 mm	60 %	1031	2.68	385
Gravel 4 - 8 mm	40 %	687	2.68	256
Water				192
Sand moisture	4 %	1031	1.00	41
Gravel moisture	2 %	687	1.00	14
Added water				137
Admixtures				
Sika® ViscoCrete®-SC	**1 %**	**4**	**1.10**	**4**
Sigunit®-L AF	**6 %**	**24**	**1.40**	**17**

Fig. 6-1: Mix design ingredients of shotcrete:
Gravel, water, cement, superplasticizer, sand (from left to right)

6.4 Material Balance of Wet Sprayed Concrete

Weight / m³	Volume / m³

Fresh Concrete
2310 kg/m³

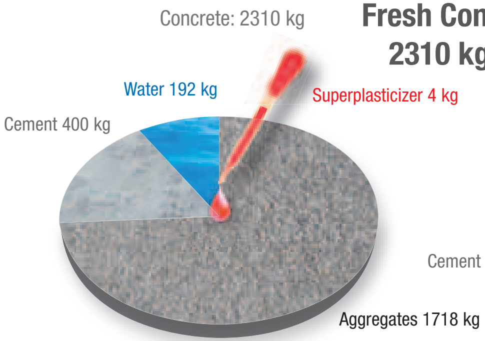


Fig. 6-2: Mix design components by weight

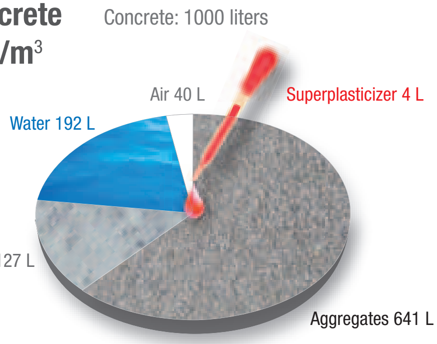


Fig. 6-3: Mix design components by volume

Spraying process

– Ø 10 % Rebound of aggregates (volume)
– Ø 4 % Cement loss (weight)
– Ø 3 % Compaction of concrete (volume)
\+ 6 % Shotcrete accelerator (cement weight)

Applied Shotcrete
2362 kg/m³

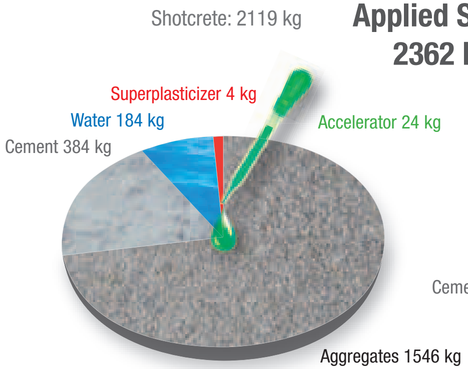


Fig. 6-4: Material balance by weight after spraying

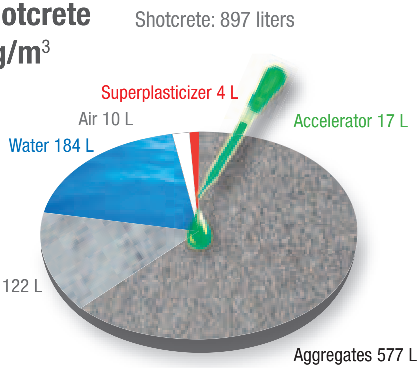


Fig. 6-5: Material balance by volume after spraying

6.5 Special Mix Designs for Wet Sprayed Concrete

Table 6-3: Recommended mix design

Mix Design	
Ingredients	**Type**
Cement	CEM I
Aggregates	0 – 8 mm
Water	No contaminants
Superplasticizer	*Sika®ViscoCrete® SC*
Accelerator	*Sigunit®-L AF*

Table 6-5: Changes in mix design for special requirements

Higher Initial Strength		
Mix Design Change	**Product**	**Effect**
+ 30 kg Cement	CEM I	Higher initial strength development
+ 2 % Accelerator	*Sigunit®-L AF*	Higher initial strength development

Higher Final Strength		
Mix Design Change	**Product**	**Effect**
+ 20 kg Silica fume	*SikaFume®*	Increased density
+ 0.2 % Superplasticizer	*Sika®ViscoCrete® SC*	Better workability / Lower water demand
- 15 kg Water	Water	Increased density

Longer Workability Time		
Mix Design Change	**Product**	**Effect**
+ 0.3 % Retarder	*SikaTard®*	Hydration retarding

Better Pumpability		
Mix Design Change	**Product**	**Effect**
+ 30 kg Fines	Fine sand / Lime stone / Fly ash	Lubrication
+ 0.5 % Pumping agent	*SikaPump®*	Decreased pump pressure
+ 0.2 % Superplasticizer	*Sika®ViscoCrete® SC*	Better workability

Higher Durability I		
Mix Design Change	**Product**	**Effect**
- 15 kg Water	Water	Increased density
+ 0.2 % Superplasticizer	*Sika®ViscoCrete® SC*	Better workability / Lower water demand

Higher Durability II		
Mix Design Change	**Product**	**Effect**
+ 30 kg Silica fume	*SikaFume®*	Increased density
+ 0.2 % Superplasticizer	*Sika®ViscoCrete® SC*	Better workability / Lower water demand

Table 6-4: Optimal shotcrete parameters

	Value
	400 kg
	1718 kg
	192 kg
	1 %
	6 %

Recommended Parameters	
Flow table spread	600 mm
Temperature	20 °C
Air voids	4%
Strength performance	J2
Workability time	2 hrs
Water / Cement	0.48

Increased Ductility I		
Mix Design Change	**Product**	**Effect**
+ 30 kg Macro steel fibers	Hooked L=35 mm, Ø 0.5 mm	Higher engery absorption
+ 0.2 % Superplasticizer	*Sika®ViscoCrete® SC*	Better workability

Increased Ductility II		
Mix Design Change	**Product**	**Effect**
+ 10 kg Macro synthetic fibers	Modified PP L=50 mm, Ø 0.5 mm	Higher engery absorption
+ 0.2 % Superplasticizer	*Sika®ViscoCrete® SC*	Better workability

Improved Fire Resistance		
Mix Design Change	**Product**	**Effect**
+ 2 kg Micro synthetic fibers	PP L=6 mm, Ø 0.04 mm	Vapor pressure reduction
+ 0.2 % Superplasticizer	*Sika®ViscoCrete® SC*	Better workability

Optimized Cost Performance I		
Mix Design Change	**Product**	**Effect**
- 70 kg Cement	CEM I	Cost reduction
+ 70 kg Additives	Lime stone / Fly ash	Substitution

Optimized Cost Performance II		
Mix Design Change	**Product**	**Effect**
- 400 kg Cement	CEM I	Cost reduction
+ 400 kg Blended cement	CEM II	Substitution

6.6 Grading Curve for Shotcrete

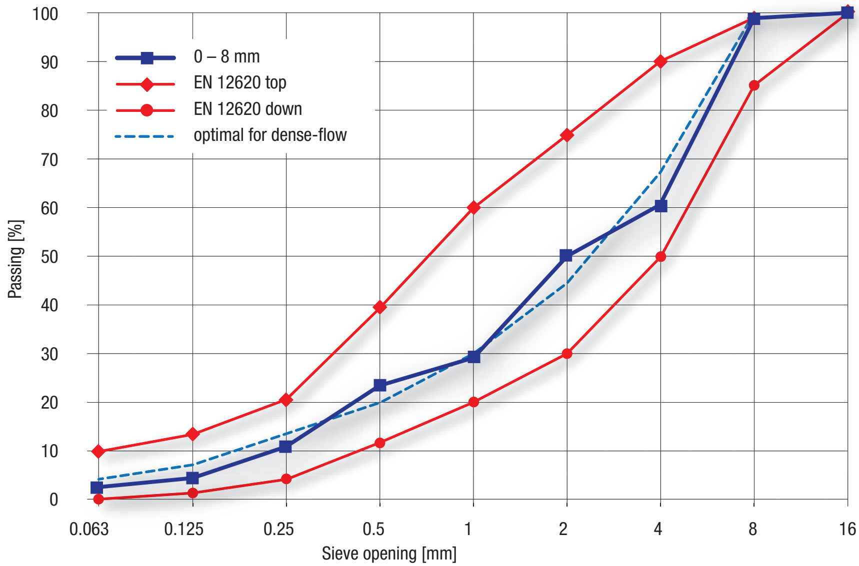


Fig. 6-6: Optimal grading curve and its limits

Table 6-6: Optimal configuration of grading curve

Component ratio	Grading curve components	Sieve opening and passing								
		0.063 mm	0.125 mm	0.25 mm	0.5 mm	1 mm	2 mm	4 mm	8 mm	16 mm
60 %	0 – 4 mm	3 %	7 %	18 %	38 %	48 %	82 %	97 %	100 %	100 %
40 %	4 – 8 mm	0 %	0 %	0 %	0 %	1 %	2 %	6 %	97 %	100 %
100 %	**0 – 8 mm**	**1.8 %**	**4.2 %**	**10.8 %**	**22.8 %**	**29.2 %**	**50.0 %**	**60.6 %**	**98.8 %**	**100 %**

6.7 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.

Table 6-7: Quality check for sprayed concrete

Process	Stage	Test Parameter	Frequency
Components	Aggregates	Moisture Grading curve Particle size	Each delivery Periodically
	Cement / Additives	Delivery documents	Each delivery
	Admixtures	Delivery documents	Each delivery
Concrete production	Mixing plant	Weighing / mixing tool	According to maintenance plan
	Concrete production	Production consistency Mix design	Each batch
	Fresh concrete testing	Water content Fresh concrete density Temperatures (concrete / air) Consistency Air content	Periodically
Transport	Hauling equipment	Maintenance	According to maintenance plan
Application	Sprayed concrete unit	Maintenance Accelerator dosage	According to maintenance plan Daily
	Sprayed concrete	Consistency Strength development Final strength Durability	According to test plan

7. Dry Sprayed Concrete

Dry sprayed concrete process 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 (oven dry) or is wetted by the inherent moisture in the aggregate. For the spraying operation, the dry sprayed concrete is mixed with water and shotcrete accelerators and then applied. Instead of shotcrete 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.

7.1 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 water inleakage
- medium spraying works
- waterproofing works
- logistics concept not time dependent (local storage)

7.2 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 stabilizing
- 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.

7.3 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 optimize 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 and particularly for dry sprayed mortar applications, i.e. gunites. These gunites are supplied in bags or by silo equipment and are stored in a silo before use, so that the site is not dependent on the aggregate obtainable locally.

7.4 Moisture Content of Aggregates

In the dry process, the inherent moisture presetting is very important for dust generation and delivery. 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 delivery 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.

7.5 Material Balance of Dry Sprayed Concrete

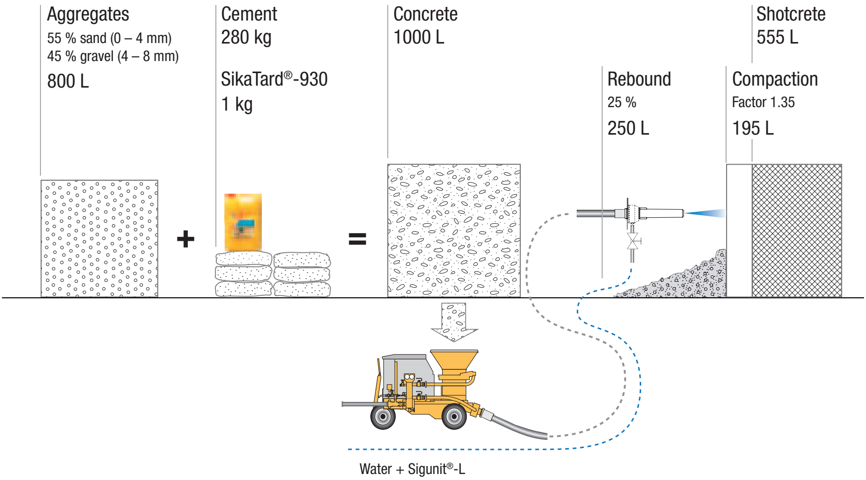


Fig. 7-1: Material balance of dry sprayed concrete

$$\text{Cement content in the applied shotcrete} = \frac{\text{cement amount} - \text{cement loss}^{(1}}{\text{volume of applied shotcrete}}$$

$$\frac{0.9 \times 280\ \text{kg/m}^3 \times 1000\ \text{L}}{555\ \text{L}} = 454\ \text{kg/m}^3$$

(1 25 % Rebound (volume) ≈ 10 % cement loss (weight)

Fig. 7-2: Cement content in applied dry shotcrete

8. Sprayed Concrete Applications

8.1 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 shotcrete 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 unstabilized 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.

8.2 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 optimize 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 inleakage, presealing or discharge of the water through drainage channels is necessary.

8.3 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
- nature of substrate or base layer
- spraying process
- spray output
- spraying direction (upward horizontally)
- obstructions (reinforcement/water)
- distance between nozzle and substrate

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.

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 maximizes adhesion and compaction and minimizes 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-fiber-reinforced sprayed concrete.

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

8.3.1 Recommended Parameters for Wet Spraying

	Parameter	**Recommendations & Limits**	Improving of ... Strength development	Pumpability	Bonding to substrate	Internal cohesion	Workability time	Mixing of accelerator and shotcrete	Environment, health & safety	Cylinder filling
Mix Design	Binder	400 – 500 kg/m³	x	x	x					
	Aggregates	60 % of 0 – 4 mm / 40 % of 4 – 8 mm / 4 – 9 % of ≤ 0.125 mm		x	x					
	Water	w/b 0.45 – 0.50	x	x		x				
	Superplasticizer	0.8 – 1.2 %	x	x			x	x		
	Accelerator	5 – 8 %, alkali free	x		x				x	
Fresh Concrete	Flow table spread	550 – 650 mm over minimum 2 hrs		x				x		x
	Slump	180 – 220 mm over minimum 2 hrs		x				x		x
	Air void content	3 – 8 %		x				x		
	Temperature	15 – 25 °C	x				x			
Application	Output	≤ 75 % of maximum output performance								x
	Distance	1.5 – 2 m								
	Angle	90°								
	Air	4 – 5 bar						x		
Condition	Substrate	cleaned and dry			x					
	Temperature	> 10 °C	x							
	Nozzleman	well-educated								
	Equipment	well-maintenanced								

				Reduction of ...											
Accelerator efficiency	Compaction of shotcrete	Quality of shotcrete	Efficiency in shotcreting	Concrete tackiness	Rebound of shotcrete	Bleeding of concrete	Blockage in the equipment	Wear in the equipment	Lamination in shotcrete caused by pulsation	Inhomogeneity in shotcrete	Admixture need (acceleration / retardation)	Adhesion failure in shotcrete	Extra time for shotcreting	Extra cost due to bad application	Dust generation
				x											
				x	x		x								
				x		x									
							x	x							
												x			
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												x			
		x	x		x						x		x	x	x
		x	x				x	x					x	x	

Application

8.3.2 Application Rules of Spraying

Fig. 8-1: Cleaning substrate from dust with water

Fig. 8-2: Filling of overbreaks

Fig. 8-3: 1st shotcrete layer – 1st excavation stabilization and adhesive bridge for the 2nd shotcrete layer

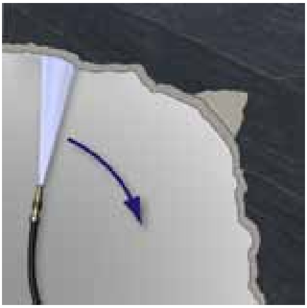

Fig. 8-4: Removing of dust with water after longer breaks

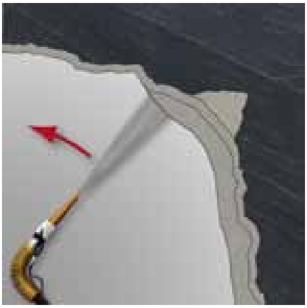

Fig. 8-5: 2nd shotcrete layer – excavation stabilization, usually together with steel reinforcement

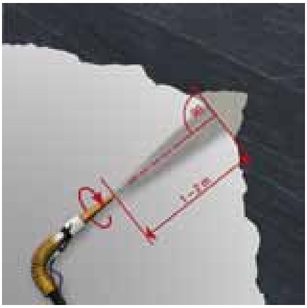

Fig. 8-6: Correct nozzle manipulation – too much air causes rebound and too high output causes lamination

8.4 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:

Table 8-2: Components which are added at nozzle

Wet Sprayed Concrete Dense-flow Process	Wet Sprayed Concrete Thin-flow Process	Dry Sprayed Concrete Thin-flow Process
• Air as carrier medium for concrete and accelerator • Sprayed concrete accelerator	• Air as carrier medium for accelerator • Sprayed concrete accelerator	• Water (carrier medium) • Sprayed concrete accelerator (water as carrier medium)

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 vapor 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.

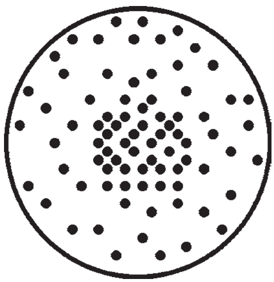

Fig. 8-7: Poor distribution of the particles over the cross-section of the jet

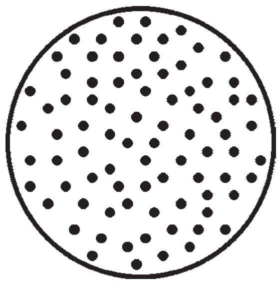

Fig. 8-8: Good distribution of the particles over the cross-section of the jet

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 are 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.

Fig. 8-9: Thin-flow nozzle

Fig. 8-10: Dense-flow nozzle

8.5 Measurement Methods

Initial and early compressive strength development of shotcrete, i.e. up to 24 h is measured using indirect methods, namely penetrometer and Hilti stud. Both methods correlate the impact of the compressive strength on the penetration of a needle. Apart from any recommendation as they are given by this method statement or local regulations (Hilti brochure, EN 14488-2, etc.) one has to keep in mind that any general correlation function describing these impacts would be just an approximation. Thus, results from these methods depend on the mix design, i.e. on the used aggregates (0–8 mm), and would not necessarily result in absolute values of the compressive strength.

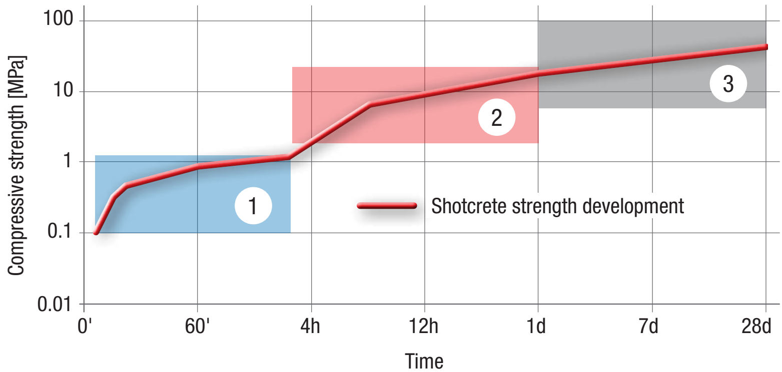

Fig. 8-11: Methods for strength development measurement

The entire compressive strength measurement of sprayed concrete requires three methods:

Table 8-3: Methods for strength development measurement

Development of		Method	Instrument	Strength	Time
1	Initial strength	needle penetration	Penetrometer	up to 1.5 MPa	0 – 3 h
2	Early strength	stud driving	Hilti DX 450-SCT	3 – 20 MPa	3 – 24 h
3	Final strength	coring	Compression testing machine	5 – 100 MPa	1 – 28 d

8.5.1 Needle Penetration Method

Results from this method are calculated from the force which is required to penetrate 15 mm of the specimen's surface using a 3 mm needle. The tip of the needle has an angle of 60°. Using this method one can manually determine the strength up to approx. 1.5 MPa.

Fig. 8-12: Penetration of freshly sprayed concrete using a digital penetrometer (Mecmesin AFG 1000)

8.5.2 Stud Driving Method (Hilti)

Compressive strengths between 3 and 20 MPa are determined by threaded studs, which are driven into the shotcrete surface. The depth of penetration results in the compressive strength according to a calibration curve.

Fig. 8-13/14: Penetration of young sprayed concrete with studs using a Hilti DX 450-SCT (left) and measurement of the stud standoff for the determination of the penetration

8.5.3 Drill Core Method

The final compressive strength is determined using concrete drill cores according EN 12504-1 “Testing concrete in structures”.

Fig. 8-15 / 16: Core drilling from sprayed concrete sample (left) and compressive strength measurement of a drill core (right)

8.5.4 Strength Classes (EN 14487-1)

The bulk of sprayed concrete is employed today in tunnel construction. Particularly here in deep mining, early strength development plays a central role. Sprayed concrete should be applied quickly in thick layers, including overhead. As a result the strengths of freshly-applied sprayed concrete are divided into three classes: J1, J2 and J3 (EN 14487).

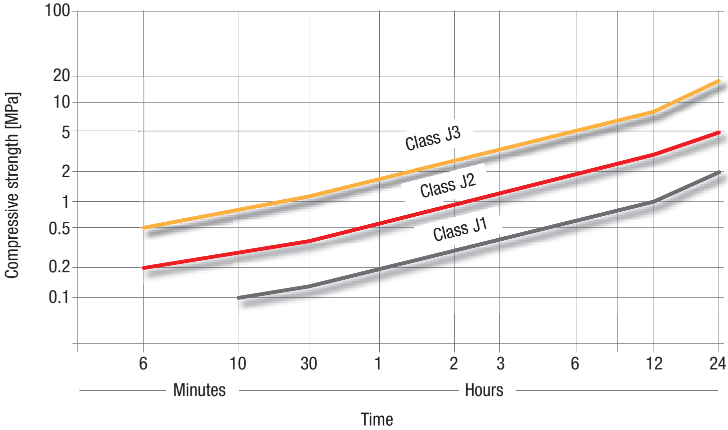

Figure 8-17: Shotcrete early strength classes according to EN 14487-1

Class J1 sprayed concrete is appropriate for application in thin layers on a dry substrate. No structural requirements are to be expected in this type of sprayed concrete during the first hours after application.

Class J2 sprayed concrete is used in applications where thicker layers have to be achieved within short time. This type of sprayed concrete can be applied over head and is suitable even at difficult circumstances, e.g. in case of slight water afflux and immediate subsequent work steps like drilling and blasting.

Class J3 sprayed concrete is used in case of highly fragile rock or strong water afflux. Due it's rapid setting, more dust and rebound occurs during the application and therefore, class J3 sprayed concrete is only used in special cases.

8.6 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 nozzleman. 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:

- nozzleman’s technical skill and experience
- spraying direction (up, down, horizontally)
- spraying parameters (air pressure, nozzle, spray output)
- spraying process (dry/wet sprayed concrete)
- sprayed concrete mix design (aggregate, grading curve, accelerator, fibers, binder)
- sprayed concrete performance (very early strength, adhesive strength, layer thickness)
- substrate condition (evenness, adhesion)

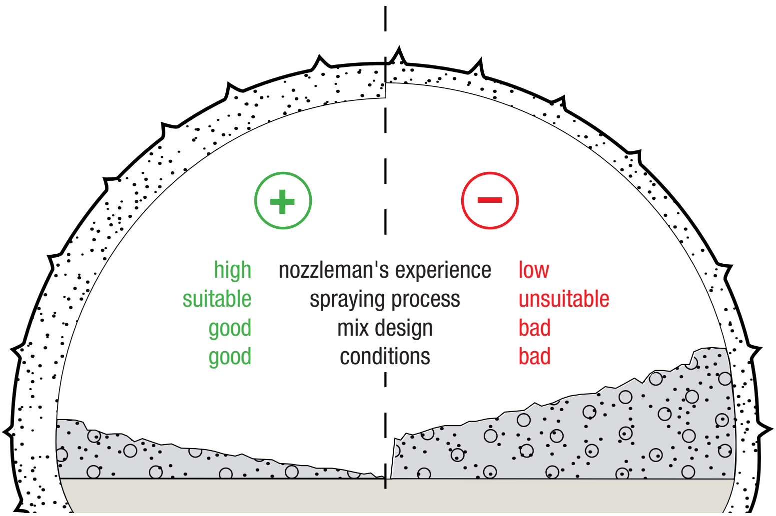

Figure 8-18: Influences on rebound

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 – 30 % for application vertically upward
- rebound with wet sprayed concrete 5 – 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 – 20 % max. of correctly treated sprayed concrete rebound can be reused without any problem.

8.7 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 (synchronized) parameters at the nozzle (air (minimization), water, accelerator (minimization))
- low-pulsation material conveyance
- use of alkali free shotcrete accelerators
- use of spray manipulators for outputs > 6 m³/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 shotcrete accelerators should be used.

8.8 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 nozzleman can only minimize spray shadows by the right choice of spraying sequence. The importance of the nozzleman as the main criterion for high-quality sprayed concrete is essential.

8.9 Mechanization / Automation

Any operation or step that is constantly repeated demands improved automation. More than 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. Mechanization 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 tunneling, 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.

9. 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.

Table 9-1: Summary of sprayed concrete processes

Medium	Material Condition	Delivery System	Carrier Medium	Method of Delivery	Additional Injection at Nozzle
Gunite (ready-mix)	oven-dry	Rotor (pneumatically)	Air	Thin-flow (Air delivery)	Water
Dry concrete	earth-moist	Rotor (pneumatically)	Air	Thin-flow (Air delivery)	Water + Accelerator
Concrete	wet	Rotor (pneumatically)	Air	Thin-flow (Air delivery)	Air + Accelerator
Concrete	wet	Pump (hydraulically)	Concrete	Dense-flow (Push delivery)	Air + Accelerator

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.

Table 9-2: Major criteria for selecting spray technique

	dry	wet
dust formation	moderate	low
rebound	moderate	low
spray output	medium	high
equipment costs	low	high
	medium quantities ⇩ small cross sections	high quantities ⇩ large cross sections

Table 9-3: Different spraying processes and their application areas

Equipment / Medium	Thin-flow: Rotor, ready-mix Mortar	Thin-flow: Rotor, earth-moist Concrete	Thin-flow: Rotor, Concrete	Dense-flow: Pump, Concrete
Requirements on Delivery				
Delivery distance > 200 m	x			x [1]
Delivery distance 40 - 200 m	x	x		x [1]
Delivery distance < 40 m	x	x	x	x
Delivery output > 10 m³/h			x	x
Delivery output 3 - 10 m³/h	x	x	x	x
Delivery output < 3 m³/h	x	x		
Delivery height > 100 m	x			x [1]
Delivery height 20 - 100 m	x	x		x [1]
Delivery height < 20 m	x	x	x	x
Conditions at Site				
Less space / narrow	x	x	x	
Operations with many interruptions	x	x	x [2]	x [2]
Need of extremely high strength performance (water inleakage / low temperature / …)	x			
Kind of Application				
Tunneling				x
Slope stabilization			x	x
Trench stabilization		x	x	x
Refurbishment	x	x		
Art building	x	x		
Sealing	x			

x = suitable [1] = high amount of waste [2] = retarded concrete

Process

9.1 Dense-flow Process

When substantial quantities must be applied the concrete is pumped through pipelines in a dense-flow to the nozzle, where it is dispersed by compressed air. Accelerator is mixed into the concrete with the compressed air. The nozzle forms the concrete-accelerator mixture to a spray jet. Thanks to the large output capacity this method is employed on one hand for excavation stabilization in tunnel construction and on the other for stabilization of large building pits.

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 synchronized with the concrete quantity so that the preset quantity of shotcrete accelerator is always added.

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

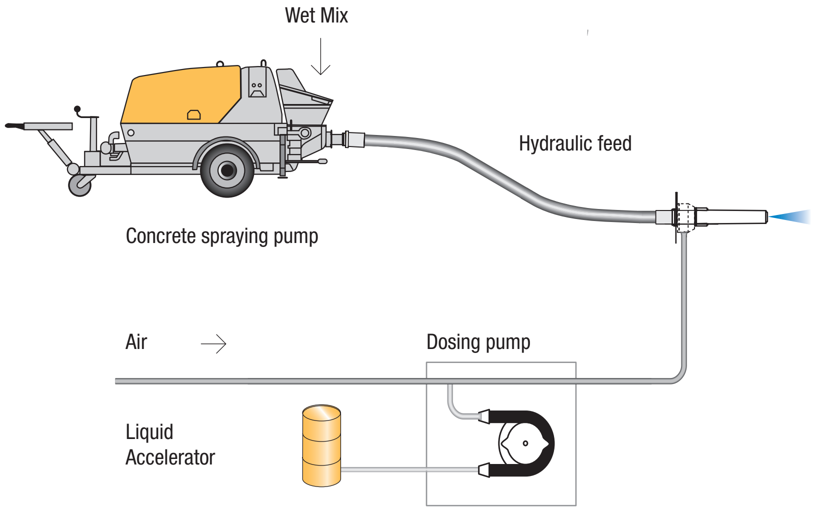

Fig. 9-1: Dense-flow process for wet sprayed concrete

9.1.1 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 in comparison to dry spraying.

- 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 durability requirements

9.1.2 Machines for Dense-flow Process

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 mechanized. 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.

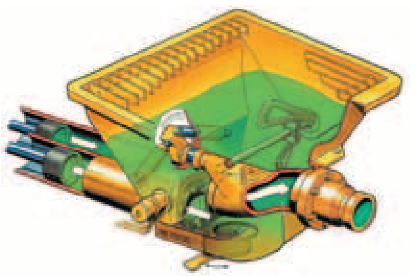

Fig. 9-2: Putzmeister double piston pump

Fig. 9-3: Sika®-PM 702 D

9.2 Thin-flow Process

Rotor machines convey concrete pneumatically by means of air (thin-flow), so that at the nozzle the concrete must not be additionally dispersed. The advantage of this method is that both wet and dry spray concrete can be applied in this manner. Since spray machines for the thin-flow process are considerably smaller than those for dense-flow processing, this technique is ideally appropriate for applications in the area of refurbishments, in which spatial limitations often impede work.

The shotcrete accelerator is fed by the metering unit through separate hoses to the nozzle. The dosage is synchronized with the concrete quantity so that the set quantity of shotcrete 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.

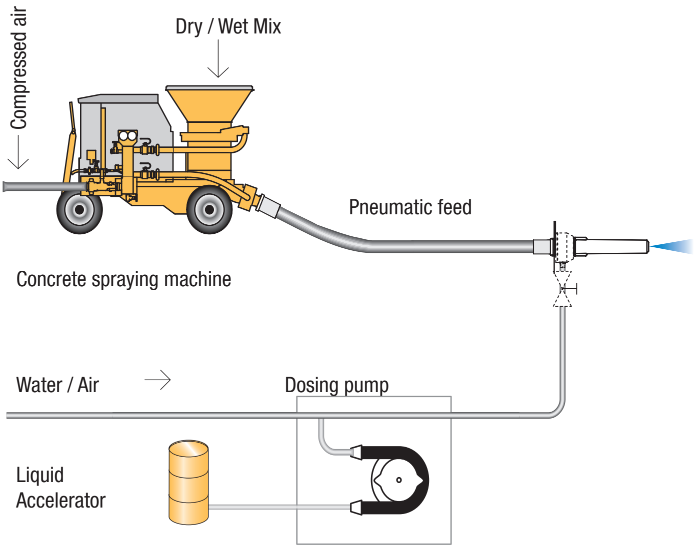

Fig. 9-4: Thin-flow process for dry or wet sprayed concrete

9.2.1 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 stabilizing
- almost unlimited holding time (availability) of silo material
- no concrete waste

With dry sprayed concrete, the economics are affected by the 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
- medium spraying works
- logistics concept not time dependent (site storage)

9.2.2 Machines for Thin-flow Process

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 nozzleman 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

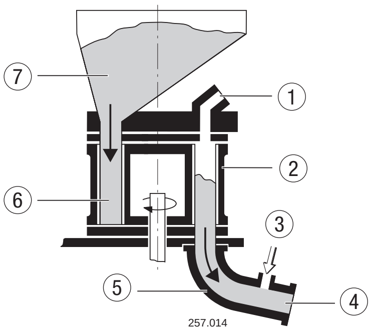

Fig. 9-5: Operating principle of the rotor-type machine

Functional Description of Aliva® Rotor Machines

The conveyor material in the filling hopper (7) slides into the rotor chamber (6). By rotating the rotor (2) and the connected top air (1) the conveyor material is conveyed into the blow-off chamber (5). With the support of the bottom air (3) the conveyor material reaches the conveyor line (4). It is conveyed from there in a thin stream to the spray nozzle, where the required additive is mixed in.

Fig. 9-6: Aliva®-237 Top

10. Concrete Spraying Equipment

10.1 Sika-Putzmeister Concrete Spraying Systems

The product range of shotcreting equipment includes mobile spraying robots as well as trailer-mounted units, with spraying reaches of up to 17 m and concrete conveying performances of up to 30 m³/h.

10.1.1 Sika®-PM 307

Track-mounted mobile spraying unit designed for automatic application of shotcrete in underground work (wet and dry process). Ideal for smaller tunnel sections and slope protection.

10.1.2 Sika®-PM 4207

This robust and compact concrete spraying machine was purpose-built for the rough working conditions of mining. The spraying arm with a vertical reach of 9 meters is designed to work in medium and small sections. The double piston concrete pump Putzmeister P715 has a maximum pumping capacity of 20 m³/h. With the possibility of an on-board screw-compressor, the machine becomes more mobile and independent in its use.

10.1.3 Sika®-PM 500

The first jointly developed concrete spraying system by the Sika-Putzmeister alliance. With a vertical spaying reach of 17 m, the Sika®-PM 500 is used for medium and large tunnel sections, caverns and high slopes. The automatic spraying arm allows an optimum maneuverability. The double piston concrete pump Putzmeister BSA 1005 has a max. pumping capacity of 30 m³/h.

10.1.4 Sika®-PM 5312

This compact machine is designed to be mounted on a 2- or 3-axle truck, which facilitates its transport to and on site on the road. Its design offers the user a perfect accessibility to the components and makes it easy to maintain. The spraying arm has a vertical reach of 14 meters, the maximum pumping capacity of the concrete pump is 30 m³/h.

10.1.5 Sika®-PM 702

Compact double piston concrete pump for hand-held concrete spraying, using the humid mixing process / dense flow method. Available with mobile chassis and liquid additive pump.

10. Concrete Spraying Systems

Fig. 10-1: Sika®-PM 4207

Fig. 10-2: Sika®-PM 500

Fig. 10-3: Sika®-PM 5312

10.2 Aliva Concrete Spraying Machines

The Aliva sprayed concrete machines and systems manufactured by Sika are designed and built to be efficient, robust and flexible, using the rotor principle for delivery. The dry-mix material is fed by compressed air in a thin stream to the spray nozzle, where water together with any additional liquid materials, such as accelerating admixtures can be mixed in. Due to its low-energy delivery, the thin stream process is also suitable for manual spraying. The Aliva equipment's self-lubricating sealing plates also reduce machine wear and so therefore also help to optimize operating costs.

10.2.1 Aliva®-237

The AL-237 is a compact concrete spraying machine for dry shotcrete as well as for small wet shotcrete application of mortars. The low filling height of the hopper allows easy handling of pre-bagged materials with little effort. The integrated FC (frequency changer) enables an infinitely variable speed of the rotor and with it the conveying capacity for each specific job. With a range of conveying capacity from 0.4 – 4.0 m^3/h the AL-237 is suitable for all kind of dry sprayed works.

10.2.2 Aliva®-257

The AL-257 is the universal machine for the application of dry and wet shotcrete in the thin-flow process. The very compact design of the machine impresses through its dimensions, weight and performance. With just over 600 kg and dimensions as little as a small dry shotcrete machine, the AL-257 fits on every job site and is easy to install and operate. With its output capacity range from 0.7 – 9.6 m^3/h (with 3 rotor sizes) the machine works on small concrete renovation work as efficient as on big slope stabilization.

10.2.3 Aliva®-267

The AL-267 is a multi-functional machine for wet and dry application of sprayed concrete in the thin-flow method. The modular construction allows the right type for all requirements. With an output capacity of 4 – 21 m^3/h the range of applications covers: tunneling, mining, rock and slope stabilization.

Fig. 10-4: Aliva®-237 Top

Fig. 10-5: Aliva®-257 Top

Fig. 10-6: Aliva®-267 Top with integrated dosing unit

10.3 Aliva TBM Spraying Robots

Together with the traditional drill and blast methods and standard excavators, excavation by tunnel boring machines (TBM) is now one of the most modern methods of tunneling. A TBM normally cuts and loosens the rock by percussive, rotary or rotary-percussive boring. Many different types of TBM are used, according to the prevailing geological and hydraulic conditions or how big the tunnel is required to be.

In principle, tunneling with a tunnel boring machine always follows the same sequence:
a) the working face is prepared with chisels, cutting wheels etc.,
b) the excavated rock is removed and brought to the surface and
c) the stabilizing work is carried out and the tunnel wall may also be lined.
During the stabilization phase c), either precast tunnel segments (prefabricated concrete units) can be installed, and / or sprayed concrete can be applied over steel reinforcement.

For stabilization by applying sprayed concrete, robotic sprayed concrete equipment is designed and produced to be mounted on and incorporated into the TBM. These large 'state of the art' systems are completely designed, developed, produced and installed by Aliva.

Fig. 10-7: Aliva® Robotic Sprayed Concrete Equipment for a TBM

10.4 Aliva 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 synchronized 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 Shotcrete Accelerators
The liquid shotcrete 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.

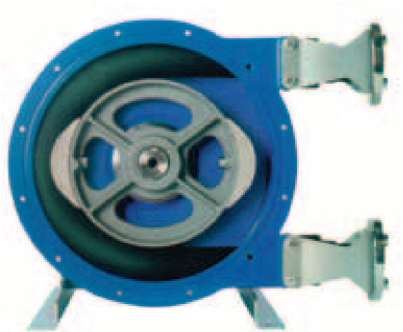

Fig. 10-8: Schematic cross-section of squeeze pump

Fig.10-9: Aliva®-403.6 Synchro

11. Waterproofing

11.1 Sikaplan® - Waterproofing Membranes

To avoid the cost of producing and installing custom made formworks for concrete lining at tunnel widenings, shotcrete can be used instead. In this method sprayed concrete is applied directly onto the polymer waterproofing membranes. To minimize shotcrete rebound, fine wire meshes are laid over the installed polymer waterproofing membranes and fixed with special anchors.
The polymer waterproofing membranes themselves are fixed to a sealing carrier layer made of sprayed concrete. This sealing carrier layer has to level the rough and uneven substrate surfaces in order to enable the waterproofing membranes to be laid without creases and tight to the substrate. There are some important technical requirements for the sealing carrier layer: free from protrusions (no steel fibers), maximum aggregate size ≤ 8 mm, compressive strength class C25/30 and minimum layer thickness ≥ 50 mm. The acceptable unevenness is showed in figure 11-1:

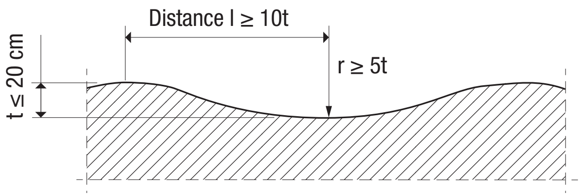

Fig. 11-1: Approvable unevenness for the sealing carrier layer according to EAG-EDT

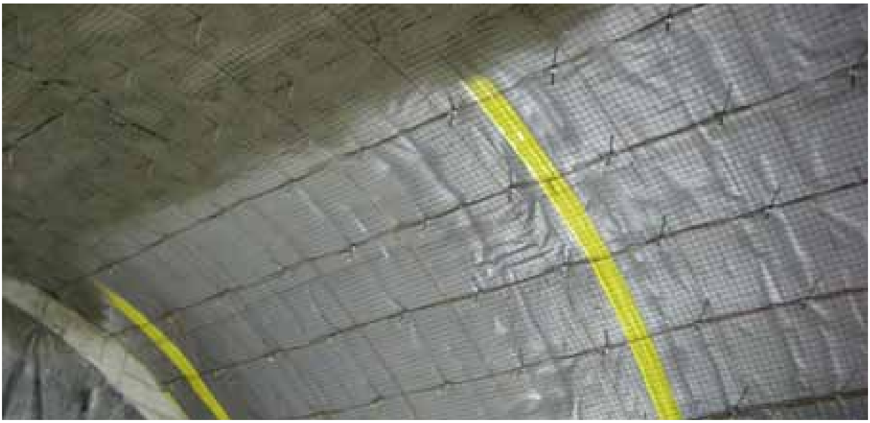

Fig. 11-2: Covering Sikaplan® with shotcrete

11.2 FlexoDrain W and Sika® Shot-3

FlexoDrain W half sections are primarily designed for use in tunnelling works where they collect and drain water from the rock. In combination with other drainage components such as branch pipes and collectors, a water drainage system of any size can be formed behind the internal surface and finish of the tunnel shell itself. The FlexoDrain W sections are fixed to the substrate with steel-bolts and the area can also be easily lined with the shotcrete layer.

Lower levels of water intrusion can be sealed using Sika® Shot-3. Sika® Shot-3 is a ready-mixed mortar with an extremely high early strength. This special pre-bagged waterproofing gunite mortar is applied by the dry spray process.

FlexoDrain W sections can also be fixed directly to the rock with sprayed Sika® Shot-3 mortar.

Fig. 11-3: Fixing of FlexoDrain W with Sika® Shot-3

12. Troubleshooting Guide

12.1 Performance Problems

Table 12-1: Troubleshooting guide for shotcrete performance problems

Problem regarding	Approach	Troubleshoot
Compaction	Optimization of matrix by adjustment of mix design	Steady sieve curve
		Content of fines > 450 kg/m³
		Addition of additives
	Increasing of compaction energy	Nozzle distance 1.5 – 2.0 m
		Air pressure 3.5 – 4.5 bar
		Cleaning of spraying head
Reaction	Improving of concrete setting and hardening	To check the accelerator consumption
		Reduction of water content
		Increasing of cement content
		Increasing of accelerator dosage
		Changing of accelerator type
		Using of cement with high C_3A content
		Using of cement with higher grinding fineness
Mixing	Reduction of stickiness	Reduction of fines content
		Increasing of water content
		Changing of superplasticizer type
		Reduction of superplasticizer dosage
	Increasing of homogeneity	Machine maintenance
		Air pressure 3.5 – 4.5 bar
		Using of spraying head rotator
		Cleaning of spraying head
Pulsation	Increasing of cylinder filling	Reduction of concrete output
		Using of free-flowing concrete (F5-F6)
		Machine maintenance
Conditions	Improving of concrete setting and hardening	Increasing of concrete temperature
		To aim a low w/c
		Increasing of cement content
		Increasing of accelerator dosage
		Using of cement with high C_3A content
		Using of cement with higher grinding fineness
		Avoiding of concrete temperature loss

12.2 Pumpability Problems

Table 12-2: Troubleshooting guide for shotcrete pumpability problems

Problem regarding	Approach	Troubleshoot
Blockage	Increasing of pumpability	Steady sieve curve
		Increasing of fines content
		Increasing of water content (avoid bleeding!)
		Increasing of superplasticizer dosage
		Using of SikaPump® (improved workability)
		Reduction of concrete output (< 10 m³/h)
		Using of SikaPump®-Start 1 (or lubrication mix)
		Increasing of air void content
		Using of SikaTard® (improved workability time)
		Extension of mixing time for fibers
Malfunction	Fault analysis according manual	Fault correction according troubleshooting guide

13. Index

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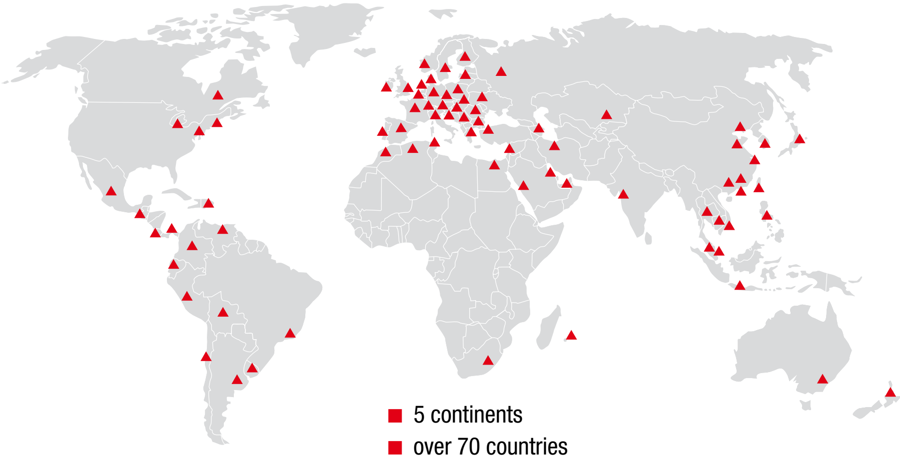

- 5 continents
- over 70 countries
- 90 production and marketing companies
- approx. 12 900 employees

Sika is a leading Swiss company, globally active in specialty chemicals. Our local presence worldwide links us directly with customers and ensures the success of Sika and its partners. Every day highly motivated people strive to provide the best customer service.

Sika Services AG
Business Unit Concrete
Tüffenwies 16
CH-8048 Zürich
Switzerland
Phone +41 58 436 40 40
Fax +41 58 436 41 50
www.sika.com

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