EUROPEAN SPECIFICATION FOR SPRAYED CONCRETE

GUIDELINES

FOR SPECIFIERS AND CONTRACTORS

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EFNARC was founded in March 1989 as the European federation of national trade associations representing producers and applicators of specialist building products. Membership has since widened and now includes many of the major European companies who have no national trade association to represent their interests either at national or European level. **EFNARC** members are active throughout all the countries of Europe, more particularly in Belgium, France, Italy, Germany, Norway, Spain, Sweden, Switzerland, and the United Kingdom.

EFNARC main activities at European level and at CEN Technical committees are in flooring, the protection and repair of concrete, in soft ground tunnelling and in sprayed concrete. It provides a common voice for the industry to make known its position and view to the European Commission departments dealing with the CPD, CEN Technical Committees and other Groups dealing with European harmonisation of Specifications, Standards, Certification and CE making relevant to our industry.

In each product area it operates through specialist Technical Committees which have been responsible for producing Specifications and Guidelines which have become recognised as essential reference documents by specifiers, contractors and material suppliers throughout Europe and beyond.

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FOREWORD

The EFNARC "European Specification for Sprayed Concrete" was published in 1996 following a draft that had been produced three years earlier. During the intervening period, over 1000 copies of the draft version had been circulated and the comments received were taken into account in the final published specification. The Specification has since been used widely and has rapidly become a standard reference document in the industry around the world.

The Specification sets out the essential requirements for a successful sprayed concrete installation. Subsequently the section of the Specification on the Execution of Spraying has been amplified and issued separately.

The Guidelines presented here provide a commentary on the Specification by giving an explanation of the requirements. To aid cross-referencing between these Guidelines and the Specification, the clause numbers are generally those of the Specification to which the Guidelines relate: those in italics are sub-divisions of the Guidelines (eg *8.2.1*).

G2 REFERENCES

The following CEN test methods represent the latest guidance relevant to sprayed concrete and supersede the list given in Section 2 of the EFNARC specification:

ISO 6784	Concrete - Determination of static modulus of elasticity in compression (1982)
prEN 12356	Testing concrete - Shape, dimensions and other requirements for test specimens and moulds
prEN 12359	Testing concrete - Determination of flexural strength of test specimens
prEN 12363	Testing concrete - Determination of density of hardened concrete
prEN 12364	Testing concrete - Determination of depth of water penetration under pressure
prEN 12378	Testing concrete - Sampling fresh concrete
prEN 12379	Testing concrete - Making and curing specimens for strength tests
prEN 12382	Testing concrete - Determination of consistency - slump test
prEN 12390	Testing concrete - Determination of compressive strength - specification for compression testing machines
prEN 12394	Testing concrete - Determination of compressive strength of test specimens
prEN 12399	Testing concrete - Determination of pull-out force
prEN 12504	Testing concrete - Cored samples - taking, examining and testing in compression
prEN 1542	Products and system for the protection and repair of concrete structures - Test methods - Pull-off test
prEN 13057	Products and system for the protection and repair of concrete structures - Test methods - Determination of Capillary water absorption

Additional references to published work:

Austin S. A. and Robins P. J. (eds) 'Sprayed Concrete: properties, design and installation', Whittles Publishing, Latheronwheel, UK (ISBN 1-870325-01-X) and McGraw Hill, USA (ISBN 0-07-057148-1), 1995.

McLeish A., 'Standard tests for repair materials and coatings for concrete', CIRIA Technical Note 139, Construction Industry Research and Information Association, London, 1993.

Opsahl O.A., 'Steel fibre reinforced for rock support', BML Report 82.205, Division of Building Materials, The Norwegian Institute of Technology, Trondheim, September 1983.

Melbye T., 'Sprayed concrete for rock support', 4th edition, January 1996

G4 CONSTITUENT MATERIALS

The constituent materials should be selected to satisfy technical and health and safety criteria. Strength requirements as well as any other requirements concerning mechanical characteristics, thickness, shape, finishing, etc. of sprayed concrete should be clearly described in the project specification.

G4.1 Cements

European Standards classify cements as different types and classes, depending on composition and performance. Economic considerations may influence the choice of cement but it has to conform to the given technical specifications. Traditional Portland cements (CEM 1) are used for most sprayed concrete applications.

Taking into consideration that every single batch of cement can differ in reactivity, depending on composition and fineness, preliminary tests are recommended to verify performance. As a general rule the higher the C_3A content and the higher the specific surface (Blaine) and the class, the higher the reactivity in terms of setting time and early strength gain, particularly in combination with set accelerators.

For certain aggressive conditions, like sulfate bearing groundwater or where there is a risk of alkali-silica reaction, a different type of cement can be specified. These cements normally have a lower C_3A content (normally less than 5%), and therefore a lower reactivity.

Modified cements or other kinds of binder can be used for sprayed concrete, once their suitability has been determined.

G4.2 Aggregates

Aggregates comprise the major component of concrete both in volume and in mass. In addition to the specified concrete strength their selection should take into account aspects such as potential rebound and good interlayer bond. Besides shape, particle size and grading, the composition, moisture content, washing treatment and organic contents should be considered. The possible susceptibility to alkali-silica reaction must also be investigated.

If wet mix sprayed concrete is used, its pumpability is an important factor and must be considered in the choice of aggregates. In practice, local restrictions and/or specific jobsite circumstances often limit the availability of suitable aggregates.

Sprayed concrete mix design differs from that of traditional concrete in terms of maximum aggregate size and grain size distribution (see 5.4).

In extreme weather conditions the temperature of the aggregate has a major influence on the final mix temperature. This has to be taken into consideration when site logistics are planned.

G4.3 Mixing water

Potable water is suitable for sprayed concrete mix. Table 1 may be used to check the suitability of other sources where there are no standards for mixing water. It should be taken into consideration that the temperature of the mixing water influences the final mix temperature.

G4.4 Steel reinforcement

Steel reinforcement is used to increase the flexural strength and reduce cracks. Steel reinforcement is normally in the form of fabric and its use is recommended for thick layers (≥ 50 mm). For most uses, reinforcing steel fabric with a mesh of 100 to 150 mm and a wire diameter of no more than 10 mm is widely accepted.

G4.5 Fibres

Fibres are generally used to increase the toughness of concrete, which is specified by residual strength or by energy absorption capacity estimated from the load-deflection curve from a beam or plate test, or to reduce or control cracking.

Fibres are normally supplied collated with a fast-acting water-soluble glue, or as uncollated individual fibres.

Table 1: Assessment of mixing water

Test	Testing method	Assessment: Suitable without comparative concrete tests	Suitable for use in certain cases[1)]	Not suitable
1. Colour	Visual test in graduated measuring vessel (wait until all suspended particles are precipitated)	colourless to slightly yellow	dark or coloured (red, green, blue)	
2. Oil and grease	Visual test	traces	oil film, oil emulsion	
3. Detergents	shake sample strongly (Half fill measuring vessel)	slightly generating foam: Foam stability ≤ 2minutes	strongly generating foam: Foam stability ≥ 2minutes	
4. Suspended particles	80 cm^3 measuring vessel	≤ 4 ml	> 4 ml	
5. Odour	Addition of HCl	none - slight	strong (e.g. hydrogen sulfide)	
6. pH value	suitable indicator	≥ 4	< 4	
7. Chloride[2)] (Cl^-)		≤ 500 mg/l		> 500 mg/l[3)]
Steel reinforced concrete		≤ 1000 mg/l		> 1000 mg/l[3)]
Not reinforced concrete		≤ 4500 mg/l	> 4500 mg/l[3)]	
8. Sulfate[2)] (SO_4^{2-})		≤ 2000 mg/l	> 2000 mg/l	
9. Sugar, Glucose[2)]		≤ 100 mg/l	> 100 mg/l	
Saccharose		≤ 100 mg/l	> 100 mg/l	
10.Phosphate (P_2O_5) [2)]		≤ 100 mg/l	> 100 mg/l	
11.Nitrate (NO_3) [2)]		≤ 500 mg/l	> 500 mg/l	
12.Zinc (Zn^{2+}) [2)]		≤ 100 mg/l	> 100 mg/l	
13.Sulfide (S^{2-}) [4)]		≤ 100 mg/l	> 100 mg/l	
14.Sodium (Na^+) [5)] Potassium (K^+)		Total ≤ 1500 mg/l		> 1500 mg/l
15.Humic substances	Add 5 ml of 4-5 % NaOH to 5 ml of mixing water. Shake well. After 3 minutes - visual test	paler than yellowish brown	darker than yellowish brown	

1) "Suitable for use in certain cases only"; means final assessment depends on case-by-case assessment and/or comparative concrete testing.
2) Use of fast test method permitted.
3) Favourable assessment may be possible in individual cases. If the entire chloride content of all concrete constituents does not exceed the limits specified in ENV 206, It 5.5.
4) Required for prestressed concrete/grouting mortar only.
5) Required only if there is a risk of alkali silica reaction.

G4.5.1 Steel fibres

Steel fibres are straight or deformed cold-drawn steel wire, straight or deformed cut sheet fibres, fibres milled from steel blocks or melt extracted fibres which can be homogeneously mixed into concrete and mortar. Steel fibres are divided into five main groups and are defined in accordance with the basic material used for the production of the fibres.

Group I	cold-drawn steel wire
Group II	cut sheet fibres
Group lll	milled from steel blocks
Group IV	melt extracted fibres
Group V	other steel fibres

G4.5.2 Synthetic fibres

Synthetic fibres are mainly produced from organic polymers, with any of several cross sections, and are sufficiently small to be randomly dispersed in a fresh concrete mix using conventional mixing procedures and sprayed with conventional equipment.

G4.6 Admixtures

A sprayed concrete mix may include admixtures such as plasticizers, retarders, etc., (just as conventional concrete does to improve the fresh mix properties and the hardened concrete quality), to ensure a good spraying application and to meet early strength requirements.

The designation 'chloride-free' for admixtures implies that the chloride ion content does not exceed 0.1% by mass of the admixture.

Plasticizers are used to achieve pumpable concretes with a minimum water content. Large additions of water should be avoided because it decreases cohesion and final strength, and has adverse effects on concrete quality (e.g. water permeability) and on the extent of rebound; it may also retard the setting time, which may also result in an increased demand for an accelerator, if used. Plasticizers based on lignosulphonates may have a set retarding effect at higher dosages and this should be taken into consideration. Because of these disadvantages, superplasticizers are preferred in many situations.

Superplasticizers are used in sprayed concrete to minimise the amount of water in the mix, thereby improving the final quality. At the dosages recommended by the supplier, they do not normally retard the setting time and can therefore be used at higher dosages than plasticizers, giving more significant water reduction. They are mainly used to give the required consistence for spraying and to aid pumpability.

Retarders are usually added to retard the setting of the concrete. High dosages of retarding admixtures can cause severe concrete stiffening, flash set and influence the early strength of the sprayed concrete. When retarders are used, the accelerator dosage rate can be higher than for conventional sprayed concrete without any retarding admixtures, in order to achieve fast setting and to spray thick layers.
With the use of retarders, preconstruction tests on site with the actual materials and mix design should be conducted prior to commencement of the work, in order to verify the dosage rate of an accelerator (early strength and ability to produce thick layers).

The use of traditional retarders is generally not recommended for sprayed concrete.

Hydration control admixtures (available commercially as proprietary materials composed of suitable blends of superplasticizers/ retarders/ stabilisers) are usually added to sprayed concrete in order to maintain workability and extend the open time during transportation and application without reducing concrete quality (e.g. consistence, setting, early and final strength).

They can maintain workability, without influencing the hydration, from a few hours to three days depending on dosage rate ("puts the concrete to sleep"). To reactivate and neutralise the hydration control effect, a suitable sprayed concrete set accelerator is added during spraying.

In general, hydration control admixtures have no negative influence on the accelerator dosage rate. The concrete mix can be reactivated at any time with the same accelerator dosage rate and with the same setting time, early and final strength development. The stored sprayed concrete should be re-mixed thoroughly before use and be protected against evaporation with a cover in order to avoid any change in the initial quality and consistence.

Thixotropic admixtures (sometimes also called Sagging prevention admixtures) may be used to reduce rebound and prevent sagging of fresh sprayed concrete. Under certain circumstances, when early loading of the sprayed concrete is not required, this type of admixture may also be used to reduce the amount of accelerator and may increase the thickness of the individual layers. These admixtures can reduce concrete slump or can be used in a combined thixotropic/accelerator admixture.

Accelerators are added to concrete during spraying to increase the stiffening rate, to produce a fast set and to get sufficient early strength development. A fast setting concrete may be necessary to build up the lining at the required thickness and to ensure overhead security. The dosage should be adjusted to ensure good cohesion between individual passes producing a single layer.

Four different types of accelerator are available commercially:

- alkali-free accelerators
- aluminates
- waterglass (silicates)
- modified silicates

Whilst alkali containing accelerators are available, *Alkali-free accelerators (see 5.5.3 for definition)* are preferred because they give a better working environment; a less hazardous material; lower risk of skin burns; have less negative impact on the environment and improve concrete durability. These accelerators have little effect on the final strength of the concrete. For permanent sprayed concrete, it is recommended to use alkali-free accelerators.

Aluminates take part in the hydraulic reactions of cement and show good stiffening and hardening effects. Significant decreases in final strength and durability occur when aluminates are overdosed. Their caustic characteristics (high pH > 12) require particular care including personal protection against eye burns, skin burns and inhalation. The use of aluminate based products should therefore be restricted.

Waterglass (silicates) generally have pH values above 12, the alkali content (Na_2O_{equiv}) being between 10% and 18%. These accelerators show very fast stiffening, but they also have secondary effects, especially when overdosed, such as significant final strength decreases, increased porosity values and efflorescence. Therefore the dosing rate has to be limited to minimise these secondary effects.

Modified silicates are special types of silicates with a pH < 11.5 and a low $Na_2O_{equiv.}$< 8.5%. They give a better working environment due to the lower pH value and less reduction in final strength compared to aluminates and traditional waterglass based products. The dosing rate has to be kept within the limits set out in the specifications.

Bond improvers - internal curing admixtures are special admixtures added to the basic mix of the sprayed concrete or at the nozzle to improve the bond between the sprayed concrete layers and/or adhesion to the substrate surface of the sprayed concrete.

They are used instead of external curing agents or other types of curing: the effect should be determined in preconstruction tests on site with the actual mix design, material and specific site conditions. Dosage rate and method of addition should be in accordance with the manufacturer's recommendations. Normally they are added to the wet mix for wet sprayed concrete.

G4.7 Additions

Additions (described in § 4.7.2 to 4.7.4) can be introduced directly into the sprayed concrete mix. These additions can be used to optimise the aggregate particle size distribution, and hence the concrete compactness, and/or improve the performances of both fresh and hardened concrete.

Many products used as additions increase the formation of the hydrating calcium silicates of the cement and these hydrates grow in a way which can improve the mechanical and physical properties. Use of pulverised fuel ash (pfa) and/or silica fume increases fresh concrete cohesion and results in a lower rebound and improved pumpability. Some slags show the opposite effect, which may need to be compensated.

Additions like pulverised fuel ash and silica fume show a pozzolanic reaction with the cement's calcium hydroxide to produce additional calcium silicates that contribute to strength development and a reduction in permeability. The pozzolanic reaction and those associated with slags have a longer time scale than the normal cement hydration, thus contributing to the long term strength and durability.

Inorganic Pigments can be specified when particular aesthetic requirements have to be met. Attention has to be paid to ensure consistent dosage and thorough dispersion to avoid significant colour variations from batch to batch. Pigments are generally inert and do not contribute to long term strength or durability.

G4.8 Curing agents

Curing agents should be specified to maximise hydration of the cement by reducing uncontrolled water evaporation.

There are two types of curing agent: *External curing agents* and *internal curing admixtures*. Both types should be used in accordance with the manufacturer's technical instructions.

External curing agents are sprayed onto the surface of the sprayed concrete shortly after it has been applied. When set accelerators are used, an external curing agent should be applied within 15 minutes after the end of spraying. When no accelerators are used it should be applied within 30 minutes.

Solvent based curing agents should be avoided, especially when used in closed spaces such as tunnels. The curing agent selected should not affect the bond of further layers/coatings or be easy to remove.

Internal curing admixtures are special admixtures added to the mix (see 4.6). Compatibility of curing agents with cements, hydraulic binders, accelerators and other admixtures should be verified in site trials. Particular care must be taken to ensure adequate mixing when used in the dry-mix process.

G5 REQUIREMENTS FOR CONCRETE COMPOSITION

G5.1 General

The concrete mix, including all the components, should satisfy the performance and Health and Safety criteria.

G5.2 Cement

The type and content of cement should be selected to meet the specified requirements for concrete strength and durability. Any material proposed as a binder which is not included in EN 197 must first be tested for suitability and should comply with the minimum requirements for traditional cement.

The cement content should normally be between 350 and 450 kg/m^3 of concrete for the dry process and between 400 and 500 kg/m^3 for the wet spraying process.

The initial setting time should be long enough to give sufficient workability, but not so prolonged as to prevent sufficient early strength development to provide safe support. Normally, the initial setting time will be between 1.5 and 3.5 hours for a cement grain fineness higher than 350 m^2/kg.

The cement performance should be evaluated by preliminary tests together with the other concrete components intended to be used on site. Its compatibility and reactivity with the admixtures should be checked during preliminary tests and for each subsequent consignment.

Maximum temperature of the cement in the mixing plant silos should be limited to 70°C and it should not exceed 50°C at the time of mixing. Cement should be fresh and stored in a dry area and/or in a suitable silo.

Where there is a risk of sulfate attack or of alkali silica reaction, special cement types (Sulfate resisting cement; SRC) should be used. These cements have a low C_3A content which minimises chemical attack, but may also show long setting and hardening times. Nevertheless, the use of an SRC does not automatically guarantee good concrete durability since physical characteristics, such as porosity and permeability of the cement matrix, will also influence the durability of the sprayed concrete. The addition of silica fume can also contribute to improved sprayed concrete durability.

G5.3 Additions

Only additions with established suitability should be used. Additions to be batched as individual components at the mixing plant should be mixed homogeneously with the other materials.

When using additions, particular attention must be given to their compatibility with the admixtures proposed to be used, especially the sprayed concrete accelerators. If in doubt, the compatibility must be verified by site trials.

Additions which have chemical reactions with cement can partially substitute the cement content. The type and amount of an addition should be carefully evaluated in preliminary tests and should comply with national standards or regulations valid in the place of use of the sprayed concrete.

Pigments can be specified as for traditional concrete and should comply with European standards or local regulations. They also should be assessed with the materials on site.

Pulverised fuel ash (Fly ash): the source of the pfa should be selected with care to ensure that the free alkali level is not excessive.

Ground granulated blastfurnace slag (ggbs): minimum value of the specific surface (Blaine) should be 450±25 m^2/kg.

Silica fume: can be added as a powder or as a slurry. The normal level of addition is 3 - 8% (by dry mass of the Portland cement) unless otherwise directed by the client or his representative. Higher levels may require additional precautions to minimise shrinkage.

The following additional requirements should be met:

- Content of amorphous SiO_2	≥ 85% (by mass)
- MgO	≤ 5%
- Ignition loss	≤ 4%
- Specific surface (BET)	> 2.10^4 m^2/kg

G5.4 Aggregates

For sprayed concrete the quality of the aggregates is of major importance, in relation to the performance of both the fresh and the hardened concrete.

The proportion of aggregate larger than 8 mm in size should not exceed 10% to minimise rebound and penetration into the already placed concrete. Aggregates in excess of 12 mm should be avoided as they can block the nozzle and cause dangerous rebound.

Aggregates based on crushed materials should be selected with care. Their angular shape may adversely influence the pumpability of the fresh concrete or the rebound of the sprayed concrete.

Aggregates should be clean and checked for potential chemical reactions like alkali silica reaction, (see G6.3), and deleterious organic materials. If the analysis indicates potential problems, the source of the aggregate should be changed or, if this is not possible, its use must be approved by the responsible engineer, after evaluation of its influence on the quality and durability of the sprayed concrete.

Figure 5.4.1 in the Specification provides guidance but the aggregate's gradation curve should be established and checks made to ensure it is compatible with the requirements of concrete strength, pumpability and rebound.

The moisture content should be taken into consideration when determining the water demand of the concrete mix. Each aggregate should be stored separately and, if possible, in a covered area. Being the major component of the concrete mix, aggregates have the major influence on the temperature of the mixed concrete. Under high or low temperature ambient conditions, aggregates should be stored in suitably protected areas and should be either cooled or heated to keep the concrete mix temperature within the specified range.

G5.5 Admixtures

G5.5.1 General

Admixtures for purposes not covered by this EFNARC specification should only be used with the written approval of the responsible authority. The contractor will be required to provide full and sufficient documentation to support the use of such admixtures.

The required characteristic values and consistency of delivery to the site should be agreed in writing with the manufacturer of each admixture before the commencement of spraying.

Storage conditions and usage of admixtures should comply fully with the manufacturer's recommendations. Many admixtures will have stability problems if exposed to frost, which can result in reduced performance. Written confirmation of the stability of admixtures with the mixing water should be obtained from the manufacturer by the contractor prior to the commencement of site trials.

Water-soluble glue or other additives used to collate steel fibres must be compatible with other sprayed concrete components, including admixtures.

All admixtures should be trial tested to evaluate performance, compatibility between the different admixtures and their overall effect on the concrete quality and durability.

Sulfate resistance of sprayed concrete should be established in reference sprayed concrete tests, if required.

The impact of admixtures on the health and safety of the operatives and on the environment should be carefully investigated. Admixture suppliers should be asked to give all necessary information and data on admixture dosage, suitability, effect on finished sprayed concrete, including previous experience, references and comprehensive safety data.

G5.5.2 superplasticizers, plasticizers, retarders, hydration control / thixotropic / bond improver and internal curing agents /- admixtures

The effects and optimum dosages of these admixtures should be determined by site trials in accordance with the specifications and should not exceed the maximum recommended by the manufacturer.
Plasticizers and retarders should be checked regularly or as required, for setting time, water reduction and development of strength as compared with the reference concrete.
Compatibilities of the admixtures with cements, binders and accelerators should be verified in site trials.

G5.5.3 Accelerators

As mentioned earlier, alkali-containing and alkali-free accelerators are both widely used. Generally, all accelerators should be used at the manufacturer's recommended dosages.

When *alkali-free accelerators* are used the following requirements should be met:

- The maximum Na_20 - equivalent of the accelerators is limited to 1.0% by mass.
- The dosage (by mass of the binder) is preferably:
  - powder accelerators: 4 - 8 %
  - liquid accelerator: 4 - 10 %
- The pH value of liquid accelerators is preferably between 2.5 and 8.

Alkali-containing accelerators should comply with the following dosage limits:

powder accelerators: 4 - 8 % (by mass of binder)
liquid accelerators: 4 - 12 % (by mass of binder)

The decrease in compressive strength (at 7 days or 28 days) of the accelerated sprayed concrete should not exceed 25% for both powder and liquid accelerators.

When aluminate accelerators are used in the presence of water with an SO_4^{2-} content of more than 600 mg/l, the content of water soluble Al_2O_3 should not exceed 0.6% by weight of cement and/or binder in the appropriate dosage. If the limit is exceeded, testing against reference sprayed concrete is to be performed at the maximum permissible site dosage.

G5.6 Fibres

Fibres may be specified in sprayed concrete to reduce the amount and spacing of traditional reinforcement or to eliminate the need for it completely. In this latter case the location of construction joints must be specified in the design, since overlapping of reinforcing fibres is not possible at construction joints.

Fibre reinforced sprayed concrete should be specifically described in terms of performance requirements by the project engineer.

Fibres differ in material, length and shape. Different fibre types normally require different addition rates, which should be recommended by the supplier of the fibres and then confirmed by site trials.

A change in the fresh concrete quality will affect the quantity of fibres rebounding and therefore the final amount of fibres in the sprayed concrete.

Fibres are normally added to concrete at the mixing plant by means of a suitable dispenser and thoroughly mixed, following the supplier's instructions.

Steel fibres are the most commonly used; fibres with lengths of 12 mm to 50 mm have been sprayed and tested. The shorter ones are easier to mix, to shoot and they rebound less: the longer ones give better results in terms of concrete toughness and post-crack resistance. Fibres are mostly specified in the length range of 25-35 mm. As a general rule the length should normally not exceed 50 mm.

Steel fibres should be stored in dry sealed containers until ready for use to protect them against corrosion, oil, grease, chlorides and deleterious materials which will reduce the efficiency of the mixing or spraying processes, or which will reduce the bond between the fibres and the sprayed concrete. Fibres which tend to form "fibre balls" during batching and mixing cannot be used.

G5.7 Consistence

The necessary concrete consistence for the wet process depends on practical aspects, like pumpability. The concrete slump should be maintained between 80 and 200 mm to produce better fresh and hardened concrete qualities. The slump of the different concrete batches should be measured and variations should be limited to ±30 mm. Alternatively, the EN 206 spread table test can be used for higher workability mixes.

Test values for concrete containing fibres may differ from those of ordinary concrete. Water reducing admixtures are used to reduce the water content and achieve the required consistence. Bleeding and segregation phenomena must always be avoided.

G5.8 Working temperature

Low temperatures retard both setting and hardening and concrete will not then achieve the early strength requirements unless higher accelerator dosages are used, but this normally reduces the final strength. High temperatures shorten workability time and accelerate concrete stiffening and setting, losing the necessary "plasticity" to get good adhesion and cohesion of sprayed concrete.

The mix temperature should preferably be in the range +10°C to +25°C. If the temperature is outside of this range, suitable measures should be taken, such as different storage for the aggregates, heating or cooling of aggregates and/or the mixing water.

G6 REQUIREMENTS FOR DURABILITY

G6.1 General

A durable concrete is one which, without deterioration, withstands the conditions for which it was designed for its required lifetime. These conditions include the environment to which the concrete is exposed and activity within the concrete itself.

The main environmental aspects are listed in Table 1: Exposure classes of prEN 206: 1997 as: carbonation, chlorides, freeze/thaw attack and chemical attack. Other sources of deterioration are weathering, abrasion and attack by aggressive liquids.

Within the concrete, durability is highly dependent on reducing the ingress of liquids and gasses that cause deterioration and on slowing down chemical reactions such as that involving the cement and certain silicas in aggregates (ASR). Low permeability is achieved mainly by having a low water content commensurate with compaction. Sprayed concrete usually has a high cement content, which results in a high water content; hence it is important to keep the water/cement ratio as low as possible.

The permeability of the concrete also governs the rate of carbonation. When the cover zone has been carbonated the reinforcing steel becomes unprotected from corrosion by the action of oxygen and water. A dense concrete will also resist the ingress of chlorides when these are in contact with the concrete, such as on bridges where de-icing salt is used and in structures close to the sea. Chlorides are agents of electrochemical corrosion of steel reinforcement.

a) Suitable constituents are governed by section 4 of the Specification. Care has to be taken when specifying combinations of admixtures, that they do not interact to the detriment of the fresh or hardened concrete. Normally, if this is the case, the admixture supplier will have relevant information that should be used to guide the producer of the concrete.

b) Requirements for performances of the final product are governed by section 9 of the Specification. Performance here also relates to all the activities within the spraying process, from mixing through to placement in position. The designer should determine the class designation, from Table 1 of pr EN 206, and then be guided by Table D1, in the determination of maximum w/c ratio and minimum cement content with the provisos noted in clause 6.4 of the Specification.

G6.2 Chloride content

As stated earlier, chloride ions are the driving force that cause rusting of reinforcing steel due to electrochemical action. And whilst salt may penetrate hardened concrete, some can be taken into fresh concrete in the mixing water and on the sand and aggregates if these are from a marine source. Table 11 of pr EN 206: 1997 gives limiting values for chloride ion Cl^- content of the concrete as placed, for plain, reinforced and prestressed concretes. The producer should satisfy himself that the total chlorides coming from all other constituents such as water, aggregates (including sand) and admixtures do not exceed these limits.

The limits given in table 11 may seem high to those familiar with the investigation of failures and the implementation of repair schemes, where values in excess of 0.2% Cl^- by mass of cement are considered unacceptable, but the crystal formation resulting from the reaction of cement and water in fresh concrete locks in a proportion of the chlorides in the original mix.

G6.3 Alkali content

Alkali-silica reaction can take place in hardened concrete when the aggregate contains a certain type of (reactive) silica, there is sufficient alkali in the mix from the cement (generally sodium and potassium oxides) and there is sufficient water available. The easiest way to overcome this is to use a low alkali cement, such as sulfate resisting Portland cement or one where Portland cement is blended with ggbs or pfa, if the aggregate to be used has reactive silica in it. Sprayed concrete generally has a high cement content which can produce a high alkali content.

For conventional concrete, local long-term experience can be taken into account, but sprayed concrete accounts for only a small percentage of the market and this experience is not likely to be available.

G6.4 Requirements related to environmental conditions

(NOTE: The reference to the European Standard should be “Section 4 of pr EN 206: 1997)

(i) At w/c ratios greater than the value quoted, the residual void content of hardened concrete increases rapidly and the strength decreases at a commensurate rate, giving a progressively less durable concrete. Note that the water content of any admixture must be taken into account when determining the total w/c ratio. This clause really only applies to wet mix concretes. With the dry mix process, the w/c ratio is mainly governed by the process itself and, as a result, is almost always lower than this value.

(ii) The minimum cement content quoted here is to ensure durability, together with the restriction on the w/c ratio. Should a higher minimum value be required by the exposure condition quoted in table 1 of section 4 of prEN 206, then that guideline must be followed. Minimum cement contents are specified in table D1 of Annex D of prEN 206 or in the National complementary standard. The limit quoted is ‘in place’, not ‘as mixed’. Whilst this limits is somewhat higher than the bare minimum, it allows for variations inherent in sprayed concrete.

(iii) Physical testing for freeze-thaw resistance is appropriate to sprayed concrete. Air content is often misleading as freezing takes place within the interstices of the concrete as well as in any entrapped air.

(iv) It has been suggested that electrochemical corrosion does not occur between fibres within the cover zone and their presence limits the action of corrosion product when they are in carbonated concrete.

G7 MIX COMPOSITION

G7.1 General

A designed mix is one where the purchaser (the designer or specifier) is responsible for specifying the required performance of the concrete and the producer (the dry mix sprayed concrete contractor) is responsible for selecting the mix proportions to produce the specified performance. A prescribed mix, where the purchaser specifies the mix proportions, is inappropriate for the dry process, considering the amount and variability of the rebound material, and hence in situ proportions. Even with the wet process there is often a certain amount of rebound material and the designed mix approach is to be preferred.

G7.2 Designed mixes

The sprayed concrete contractor has the freedom to produce his own concrete, provided it meets the performance requirements specified to him. As listed in this clause, the specifier can require the hardened concrete to have various physical characteristics, which are checked by the appropriate testing regime covered in section 9 of the Specification.

G7.3 Prescribed mixes

The usual procedure for prescribed mixes for conventional concrete is for the purchaser to specify the mix proportions. With any type of sprayed concrete an experienced contractor has knowledge of the process and the materials, their interactions and the expected end product. Once again, the amount of rebound can be variable yet critical and one of the main reasons for not using a prescribed mix in the dry process is the uncertainty of the eventual mix proportions. It is therefore recommended that the specifier takes account of this knowledge and is guided by the contractor when determining the concrete mix for a particular application. Note that no mention is made of strength; there is a danger of over-specifying concrete in that minimum cement strength class coupled with a maximum w/c ratio is sufficient to ensure a particular minimum strength of concrete.

For structural work, prescribed mixes should be avoided or otherwise there should be frequent verification tests on actual performance.

G7.4 Combined mix design

As noted above, there are dangers in over-specifying concrete and the flexibility allowed by this clause should only be needed on rare occasions.

G8 EXECUTION OF SPRAYING

These Guidelines relate to the revised Section 8 which has been issued as a separate and later document to the Specification.

G8.1 Preparatory work

Good preparation is essential to sprayed concrete work. The clauses in this section are therefore particularly important and must be implemented.

G8.1.1 Substrate

Sprayed concrete is normally placed in thin layers compared to conventional concrete, which makes it vulnerable to heat loss. If the substrate is cold at the time of spraying it will quickly rob the sprayed concrete of its heat and will retard or stop the hydration of the cement. Strong winds rapidly evaporate water from concrete surfaces, yet in sprayed concrete the water content is usually low, with little tolerance on loss to the atmosphere. Because sprayed concrete has a large surface to volume ratio and because it is built up in layers, the effect of heavy rain is detrimental.

G8.1.2 For rock support

For tunnel headings and for caverns being driven through rock, the rock face is generally freshly broken and solid. Adhesion becomes problematic in the case of friable, flaky or shale-type stone and rock surfaces that suffer decomposition on exposure to air or moisture. Outdoor rock surfaces are generally badly soiled and weathered to various depths. Such surfaces should be thoroughly and painstakingly cleaned if the sprayed concrete is to adhere properly. They should be washed; which may require the use of high-pressure water, steam or grit-blasting.

There are many ways of dealing with water ingress and include grouting, drilled holes, channels, chases, pipes. Unless it is stopped, the water is normally taken to the invert or to the groundwater drainage system.

G8.1.3 For concrete repair

Removal of concrete
The edges of a cut-out are required to be at 45° to avoid rebound being trapped in right-angled corners and thus ensure a proper build up during spraying.

It has been found in practice that a minimum gap of 20 mm is required behind rebars to ensure complete encapsulation during spraying. This, of course, is affected by the size of the bar and the technique employed by the nozzleman.

When removing concrete with chisels it has been found that because the rebars are hidden, they can be damaged easily, reducing their cross-sectional area. The use of chisels in the vicinity of and directly on the rebars should not be permitted. Hydrodemolition is the preferred method for concrete removal as, with any form of mechanical removal, it is possible to create micro-cracking in the substrate and to damage the reinforcement.

The specification for the work should indicate whether hydrodemolition should be carried out within specified areas and to specified depths, or if selective hydrodemolition of inferior concrete should be undertaken. Fully automated robots are preferred for selective hydrodemolition and the equipment should be calibrated using a reference area. The calibration should include water flow, water pressure, size of nozzle and dynamic pattern. Calibration should be done using the specified depth of demolition. The results from the reference area should be approved by the Engineer prior to further demolition.

After hydrodemolition, the resulting concrete should have no loose concrete on it and the coarse aggregate should be soundly embedded (when knocked with a hammer it should split rather than come loose) and pin holes should cover less than 5% of the area.

Rebars
Hydrodemolition should provide the required cleanliness and no additional rebar cleaning should be necessary provided that the spraying is carried out within the time agreed with, or specified by, the Engineer: dirt and rust being the two main factors. Otherwise, rebars should be cleaned prior to spraying,

by grit blasting or by high pressure water cleaning. In marine or other chloride-contaminated environments special precautions will need to be taken.

It is normal for rebars with reduced cross-sectional areas to have additional bars welded or tied in, as appropriate and as determined by the Engineer.

G8.1.4 Quantities

Rock quality is assessed and recorded so that it can be used as a basis for the evaluation of the total concrete volume needed for rock support.

Areas to be sprayed should be designated by profile number and location within the profile. A volume estimate should be based on area, specified average thickness and the roughness factor. The roughness factor is empirical and gives an overall characteristic of the:

- actual rock surface divided by the theoretical area, and
- volume for filling hollows and cracks versus volume for even distribution.

The roughness factor varies from 1.0 for full face tunnels to 1.3 -1.8 for blasted tunnels. The factor may further vary depending on layer thickness. (Ref: Norwegian Sprayed Concrete Guidelines, Publication No. 7)

G8.2 Spraying operations

G8.2.1 Spraying technique

The sole objective of sprayed concrete is to obtain a compact, dense and firmly adhering layer with the lowest possible rebound loss. Rebound is affected by a number of factors, such as the force and impingement angle of the jet. Since the velocity of the material emerging from the nozzle is usually not variable, the force of impact depends on the distance between the nozzle and the substrate surface, and on the angle of incidence. If this distance is too short, it will not be possible to build up a layer on the surface because the deposited material will be continuously washed away by the jet. If the distance is too great, the impact force will be too weak to provide proper adhesion and compaction of the concrete. In either case, the rebound quantity will be excessive, because little material will adhere to the surface. Conversely, the rebound is kept to a minimum when the distance between the nozzle and the substrate surface stands in proper relation to the exit velocity of the material. It is very important for the nozzleman to maintain this distance precisely.

Recommended spraying distances:

	dry-mix	wet-mix
Repair works	0.5-1.0 m	0.5-1.0 m
Rock support, manual	---	0.5-1.5 m
Rock support, robot	---	1.0-2.0 m

The angle of rebound of the mix from the substrate surface is the same as the angle at which it strikes it. The more oblique the angle of impingement of the jet, the more material will be lost. Hence the nozzle should always be held at right angles to the substrate surface, except as necessary to ensure proper embedding of items such as lattice girders and reinforcing bars.

Strength, compaction and adhesion of the sprayed concrete are greatly affected by cavities and porosity. Defects of this type occur when rebound collects, for instance, on rock projections or in fillets, or when the encasement of reinforcing bars is inadequate. Such defects behind reinforcing bars are referred to as 'shadowing'. It is the duty of the nozzleman to manipulate the nozzle skilfully enough to avoid any rebound pockets or accumulations of rebound. Because it is not always possible to spray in the rebound compactly or blow it away with the jet, the hose-dragger often has to assist by removing the rebound continuously with a blow pipe.

G8.2.1.1 Layer thickness

If the freshly sprayed concrete is to adhere properly to the substrate, its dead weight should exceed neither the internal cohesion nor the strength of adhesion to the surface. If the fresh sprayed concrete layer is too thick, and therefore too heavy, it will break away from the surface under its own weight. In the case of overhead work, any poorly adhering sprayed concrete layer will fall down. Judgement is required in the case of vertical or sharply inclined surfaces. A thick, and hence excessively heavy, sprayed concrete layer applied to such a surface will often sag only slightly, without falling off, because a self-supporting effect acts in such cases. Serious defects of this type can easily go unnoticed. They are discovered only after the sprayed concrete has hardened, when the material is checked for cavities and lack of bond with the hammer.

The use of a sprayed concrete set accelerating admixture allows a thicker layer to be applied in each pass.

G8.2.1.2 Spraying with steel fibres

Depending on the required final thickness, the application of steel fibre reinforced sprayed concrete may be undertaken in two phases to minimise rebound, the first phase being a 50 mm layer. For repair works refer to *8.2.6.*

G8.2.1.3 Measurement of rebound

When required, the rebound is checked by spraying a controlled volume of at least 0.75 m^3 and collecting the rebound. A ground area of 40-50 m^2 is covered with plastic sheeting. The sprayed concrete should be placed in one continuous operation, with a total thickness of 40-60 mm, built up in two layers of 20-30 mm. At the beginning of the test the pump or gun hopper must be full, and the level in the hopper must be identical at the end of spraying. The rebound is collected from the plastic sheeting and weighed. Its quantity is recorded as the percentage by mass of the total sprayed concrete.

G8.2.6 Spraying for repair works

Recommended thickness of sprayed layers - without the use of any type of set accelerating admixture:

- Behind and around reinforcing bars:
  - Overhead faces: 10 mm past the rebars
  - Vertical faces: 20 mm past the rebars
- Additional layers or where there are no rebars:
  - Overhead faces: max. 30 mm
  - Vertical faces: max. 50 mm

Prior to the application of subsequent layers the sprayed concrete of the previous layer should have reached adequate strength. At a temperature of approx. 20ºC and without the use of any type of sprayed concrete set accelerating admixture, the waiting time will be approx. 3-5 hours.

Due to the increased risk of not completely encased reinforcement and poorly compacted concrete, steel fibres should not be used when spraying behind rebars, and special precautions should be taken when using other types of fibres. Steel fibres may be used when spraying outside rebars.

Reinforcement cover should be controlled either by establishing a reference plane prior to spraying or by the use of a cover meter after spraying. The method should be as agreed by the Engineer.

Where finishing and alignment control is required, this should be carried out using a screed-board or piano wires.

For structures subject to chloride exposure, i.e. sea water or road salting, the curing agent should be capable of forming a barrier against chloride intrusion.

G8.2.7 Proficiency of operators

Nozzlemen shall hold relevant certificates of competence issued by the Contractor or written evidence of previous satisfactory work indicating compliance with CITB-NVQ scheme (UK), ACI 506.3R-82 (USA) or similar national standards to the approval of the Engineer.

G8.3 Equipment

G8.3.2 Wet-mix process

Pumping equipment should ensure the continuous conveyance of base concrete with minimal pulsation. The recommended pump types are as follows:
- Piston
- Mono
- Peristaltic

In general, the air compressor should have a capacity of 1 m^3/min at 700 kPa (7 bar) for each m^3/hr of spraying capacity and its supply rate should be controlled by the operator.

The compressed air demand may increase by as much as 50% depending on how well lines and nozzle are suited to the spraying capacity. Too low an air flow results in low spraying velocity and hence in poor compaction, poor density and low strength.

G8.3.3 Dry-mix process

The recommended dry-spraying machines are as follows:

- Wheel feed

The feeder of the wheel feed pump is located inside the pressure chamber into which the dry material is fed. The output is varied by adjusting the rotation speed of the cell feeder and the wheel.

- Rotor machine

With the rotor machine, the dry mix is filled into the feed hopper. As the rotor revolves, the mix falls under its own weight, through a feed slot, in turn into each of the rotor chambers below. While one of the chambers is being filled, compressed air is blown from above into another (full) chamber. The mix is discharged into the outlet opening and blown at a pressure of 3-6 bar through the conveying pipeline to the spraying nozzle where the mixing water is added. The top and bottom of the rotor are sealed with rubber discs.

Pulsation of the concrete flow created by the rotor principle is undesirable and can be reduced by extending the hose line and by the selection of the correct rotor type (volume of rotor chambers). The output is varied by adjusting the speed of revolution and the volume of the rotor chamber.

Common to both types is that the diameters of line and nozzle must be suited to the spraying capacity.

- Double chamber type

The double chamber system consists of two connected chambers arranged one above the other, with the discharge outlet at the bottom of the lower chamber. The procedure starts with the dry mix being fed into the upper chamber while the bell valve between the two chambers is closed. Next, the feed-opening is sealed and the pressure in the upper chamber is equalised to that of the lower one. The valve between the two chambers is then opened, allowing the mix to pass from the upper into the lower chamber. When this is completed, the valve between the two chambers is closed and the pressure is released in the upper chamber to permit re-opening of the charging port. In the meantime, the dry mix is discharged from the lower chamber by a pneumatically driven feed wheel and is picked up by the air stream in the discharge line.

Compressed air
The necessary air volume is governed by the required production rate and length of hose line. As a rough guide, 2m^3/min of compressed air is required per m^3/h of spraying capacity. The air velocity in the hose line should be 40-60 m/s. To obtain an even material flow, the length of the hose line should be not less than approx. 30 m.

For wheel feed the air pressure in the pressure chamber should be approx. 60 kPa (0.6 bar) at free air flow through an open hose line. When dry materials are added the pressure will increase to approx. 230 kPa (2.3 bar). As a rough guide, the air pressure should be increased by approx.:
- 2.2 kPa (0.022 bar) per m for horizontal conveying
- 4.5 kPa (0.045 bar) per m for vertical conveying

The maximum conveying distance is approx. 500 m for horizontal lines and 100 m for vertical lines.

Mixing water
The water is added at the nozzle at a pressure of 400-4000 kPa (4-40 bar), at somewhat more than the theoretical minimum water/cement ratio necessary for hydration of the cement.

Recommended line and nozzle dimensions

Sprayed concrete output [m^3/hr]	Line and nozzle diameter [mm]	Compressed air requirement [m^3/min]
1	25	3
2	32	4-5
4	40	8
6	50	12
9	65	17-20

G8.4 Application of wet-mix sprayed concrete used for rock support

G8.4.1 General

- When the concrete arrives at the work location, both the slump and the temperature should be measured and recorded in the delivery note and on a special form. After interruptions of more than 15 minutes, the slump should be checked before starting the spraying operation again.
- The location and operator who is spraying the concrete should also be noted on the special form.
- The recommended slump should be between 100 and 200 mm.
- Before starting up, a cementitious slurry should be mixed and fed into the concrete hose.
- Spraying should always start from the bottom to avoid any entrapment of rebound.
- Rock support should always start by filling holes and cracks in the surface. In practice this is very important, as it stops any movement of the crack.
- The distance between the nozzle and the surface to be sprayed should be kept in accordance with the recommendations of G8.2.1. When reducing the spraying distance, the nozzle should be moved faster.
- The nozzle should point to the surface at a right angle to ensure optimal compaction and fibre orientation. If kept in a wrong direction, this results in a poorer concrete with a low density.
- The relationship between air pressure, accelerator and concrete stream should always be observed. With high dosages of accelerator, the sprayed concrete surface will be 'dead' (no movement because of flash set); the coarse aggregates will not penetrate into the sprayed concrete surface and will return as rebound; the concrete stream will be more dusty than normal. High over-dose of accelerator may give a wet appearance to the sprayed concrete on the wall, but setting is very quick and the surface will look like glass. 'Shooting' in the nozzle means too much accelerator. The dosage of accelerator should be kept at a low level, between the limits specified by the supplier. On a vertical wall less accelerator can be used than for the roof surface.
- The first layer should be thin to avoid sagging of the fresh concrete, preferably about 60 mm (max. 100 mm). The following layers should be 50–200 mm, depending on the final thickness (and on the type of set accelerating admixture used).

As far as practicable all sprayed concrete for rock support should be applied using remote controlled spraying equipment appropriate to particular applications. Remote controlled spraying equipment should be provided with as long reach as possible and allow the operator to observe the nozzle at all times during spraying from a position of safety and provide the operator with full and effective control of the nozzle articulation and other functions.

G8.4.2 Clay zones

(Ref: Norwegian Sprayed Concrete Guidelines, Publication No. 7)
Lesser clay zones may be safely stabilised with steel fibre reinforced sprayed concrete in combination with bolts and strips. The sprayed concrete will then form a strip-reinforced bridge across the clay zone and is anchored by bolts in solid rock on either side.

The width of the clay zone and possible presence of swelling minerals will determine if sprayed concrete or poured concrete is more appropriate. If the clay zone exceeds 1 m or runs at a sharp angle, a specialist should be consulted. If swelling of any significance is anticipated, a cushion of compressive material (e.g. mineral wool) may be placed between the clay and the sprayed concrete.

If the clay zone has a limited swelling pressure, or if the zone mainly consists of crushed rock, it may be suitable to install reinforced sprayed concrete ribs rather than using poured concrete. The rebar diameter may vary, but mostly a diameter of 20 mm is used.

The width, thickness and spacing of the ribs depend on the anticipated support stress. The first layer usually is 100 -150 mm and may be steel fibre reinforced. It is also used for levelling. The next layer may also be fibre reinforced provided that spraying is not done against rebars placed after the application of the first layer.

Sprayed concrete applied after placement of rebars should be done with care especially when fibre reinforced due to the increased risk of incompletely encased reinforcement and poorly compacted concrete.

G8.4.3 Spraying on rock subject to high pressure

(Ref: Norwegian Sprayed Concrete Guidelines, Publication No. 7)
Under conditions of rock scaling due to high rock pressure, steel fibre reinforced sprayed concrete in combination with bolts is often used. It is important to place the steel plates of the bolts on the surface of the sprayed concrete and that large plates be used in order to spread the pressure and thus avoid cracking of the sprayed concrete. Usually, triangular plates with sides of 400-500 mm are used. Sprayed concrete bonds poorly to steel plates.

It is important to carry out the sprayed concrete application in even layers to avoid shear failure and scaling. Under such circumstances the concrete deformation energy and plastic deformation capacity is more significant than the compressive strength.

G8.4.4 Thickness control for rock support

Where specified on the drawings the minimum layer thickness should be controlled by proprietary fluorescent plastic thickness control markers pushed into an initial sprayed concrete coating. Thickness control markers should be used at a frequency of at least one marker per 2 m^2 of sprayed area and should in general be located at points of maximum protrusion of the excavated surface into the tunnel void.

Thickness control markers should be removed from sprayed concrete immediately after spraying to leave open small holes through the thickness of the sprayed concrete as a permanent pressure relief provision. Detailed proposals of type, material and method of use of thickness control markers should be submitted by the Contractor to the Engineer for his approval.

The Contractor should verify the thickness of any sprayed concrete layer by drilling 25 mm diameter percussion probe holes at any location and at an agreed time if required to do so by the Engineer. The Contractor should provide every necessary facility to the Engineer to allow inspection of the probe holes. Inspection holes may be left open subject to the approval of the Engineer.

G8.4.5 Rounding of edges and corners for rock support

Sprayed concrete may follow the contours of the rock surface with appropriate rounding of edges and corners, provided that protruding blocks of sound rock, still firmly part of the rock mass, have a sufficient sprayed concrete cover.

G8.5 Scaffolding

Scaffolding should be of sufficient width to allow the nozzleman to be correctly located.

G9 REQUIREMENTS FOR FINAL PRODUCT

G9.1 Compressive strength

G9.1.1 Concrete strength classification

Concrete for spraying applications may be classified otherwise than as stated in EN 206, but should be as close to the standard as possible. Full compliance cannot be obtained due to the specific requirements of the spraying operation.

In addition to the initial strength potential, the final strength is influenced by the use of sprayed concrete set accelerating admixtures. The spraying operation itself and the degree of compaction also has a considerable effect.

The required minimum strength should be according to this Specification: 9.1, tables 9.1.1 and 9.1.2, as shown below:

```
40 MPa x 0.8 x 0.84 = 27 MPa (see Specification: table 9.1.2)
   |       |       |
   |       |       |_ conversion factor for in situ sampling
   |       |
   |       |_ conversion factor for cube/cylinder specimen
   |
   |_ requirement for cast cube specimen
```

The characteristic strength for cast samples can be calculated and evaluated. For drilled cores the required minimum (according to Specification, table 9.1.1) applies to each sample consisting of a minimum of 3 specimens.

It may be desired to base the strength control on testing after 7 days instead of 28 days. The early strength depends on temperature as well as cement type, additives and the use of silica fume, and the correlation between the 7 day and the 28 day strengths should be established in each case. The strength reduction caused by the use of accelerator should be taken into account during the planning.

Unless otherwise agreed between the sprayed concrete contractor and the concrete supplier, the concrete as delivered at site should have a minimum strength classification as shown in the Specification: tables 9.1.1 and 9.1.2.

G9.1.2 Compressive strength tests

Compressive strength tests should be carried out in accordance with the Specification: 10.1, 10.2.

24 hour testing should only be carried out where sprayed concrete set accelerating admixtures have been used (rock support). For repair works and where no set accelerating admixture has been used, earliest testing should begin at 3 days.

Tests for 1 day strength should be carried out at 24 hours ±2 hours. Cores required for 28 day strength tests should be obtained at the same time as those for 1 and/or 7 day tests and stored in the laboratory in accordance with this Specification: 10.1, 10.2.

The frequency of coring should be such as to obtain 3 cores each for 1, 3, 7 and 28 day strength. The testing intervals depend on the type of work and have to be agreed/specified by the Engineer. Depending on the compliance of test results, circumstances of application and importance of construction, the frequency may be reduced or increased as approved or directed by the Engineer. The cores should be cored through the whole thickness of the sprayed concrete and visually inspected to verify that the sprayed concrete is dense and homogeneous without segregation of aggregate and/or fibre or other visible imperfections.

For repair works it is recommended to only measure the compressive strength on cores taken from test panels. In the event of failure to meet the requirements, the Engineer may require verification from a core taken from the permanent works. Precaution must be taken to avoid damage to the structural reinforcement during coring.

G9.2 Flexural strength

When specified, the flexural strength shall be determined in accordance with 10.3.2. Unless otherwise required, tests shall normally be performed at 28 days. When the flexural strength is specified for fibre reinforced concrete, it shall be determined from the first peak strength in the load deflection curve.

The flexural strength shall normally be determined as the mean value of three test specimens. Testing intervals depend on the type of work and should be agreed with, or specified by, the Engineer.

G9.3 Toughness

Toughness is the ability of fibre reinforced concrete to sustain loads after cracking of the concrete. It is the most important characteristic of fibre reinforced concrete and is specified either by residual strength (from a beam test) or by energy absorption capacity (from a plate test).

G9.3.2 Residual strength class

The residual strength shall be determined in accordance with 10.3.3. When the residual strength class of fibre reinforced concrete is specified, it shall be measured for a specified deformation level, that is up to a specified beam deflection. (see Figure 9.3.1 and Table 9.3.1) The stress deflection curve shall be determined for three samples. Testing intervals depend on the type of work and should be agreed with, or specified by, the Engineer. Unless otherwise required, tests shall normally be performed at 28 days.

G9.3.3 Energy absorption class

The energy absorption shall be determined in accordance with 10.4. the energy absorption shall be determined on three samples and the mean value shall meet the specified energy absorption for the required class. Testing intervals depend on the type of work and should be agreed with, or specified by, the Engineer. Unless otherwise required, tests shall normally be performed at 28 days.

G9.4 Modulus of elasticity

The modulus of elasticity may be specified by the Engineer, particularly in repair work where a close match with that of the substrate is desirable. The specification refers to ISO 6789 for concrete, but standard tests also exist for repair materials.

G9.5 Bond strength

Random checking by tapping on the sprayed concrete surface with a hammer, crow bar or similar is a simple and practical way to check bond to the substrate. However, in order to assess the actual bond values, drilled cores have to be tested

Testing should consist of one test (meaning the average of results on 6 specimens from the same general area of the works as approved by the Engineer). Testing intervals depend on the type of work and should be agreed with, or specified by, the Engineer.

Testing of the strength of the bond between sprayed concrete and rock should be carried out by testing of substrate/sprayed concrete bonded cores in situ (by a core pull off test) or in the laboratory (by a tension test)).

The apparatus to carry out the tests and detailed test methods should be approved by the Engineer. Tests should be carried out on cores greater than 50 mm and less than or equal to 60 mm in diameter. Drilling for in situ testing must penetrate the substrate by at least 15 mm. Special precautions should be taken that the core is drilled at a 90° angle to the plane of application in order to ensure axial loading. For repair works precaution must be taken to avoid damage to the structural reinforcement during coring.

Cores taken for laboratory testing should be cured in a manner representative of site conditions (not in water) and protected until the time of testing.

G9.6 Fibre content

The addition of steel fibres significantly improves the concrete toughness and may have a positive effect on the bond between concrete and rock (Ref. Opsahl). The flexural, tensile and compressive strengths as measured in laboratory tests are only marginally influenced provided there is no change in the mass ratio. Compared to laboratory tests, full scale tests give similar values for the flexural and tensile strengths of fibre reinforced concrete while it is substantially reduced for non reinforced concrete. The steel fibres should be kept dry during storage to avoid corrosion and balling.

For sprayed concrete in sub-sea tunnels or other marine environments, galvanised or stainless steel fibres are used in some cases to obtain extra protection against corrosion. This, however, involves the risk of gas formation caused by a chemical reaction between zinc and the de-chromatised cement paste. Galvanised steel fibres may also be used for temporary support in coal mining.

The reinforcing effect of steel fibres is different from the effect of rebars or fabric reinforcement. The main effects of steel fibre reinforcement are the enhancement of:

- The bond between concrete and substrate
- The toughness, i.e. load-bearing capacity subsequent to initial cracking.

Polypropylene fibres are little used in sprayed concrete for rock support. They are, however, widely used in sprayed concrete repair where they are mainly used for crack reduction. Polypropylene fibres are available in different types. Common practical dosage is 0.75-1 kg/m^3; mixes with higher dosages are difficult to spray because of balling and poor compaction.

G9.7 Permeability

Three 150 mm diameter cores must be obtained by dry rotary diamond drilling from each site trial in accordance with this Specification: 9.7.

For each core the following information should be recorded:

- Date of coring
- Core number
- Direction of spray

For repair works precaution must be taken to avoid damage to the structural reinforcement during coring.

G9.8 Frost resistance

If frost resistance is specified, the test methods and requirements set out in this Specification: 9.8 should be followed.

G10 TEST METHODS

Whilst the nature of sprayed concrete requires specific test methods, the majority of relevant properties can be measured by well established methods. The crucial difference is mainly in the making and preparation of the sample. Samples for all tests can be taken from a test panel sprayed during the works. Alternatively some tests can be carried out on samples taken from the in situ sprayed concrete, which have the advantage of being more representative. The option largely unavailable to engineers is to prepare samples cast into steel moulds, because of the difficulty of spraying a properly compacted sample into a confined space. Samples must therefore be cut by sawing or coring from a test panel or from the in situ material.

European standard methods appropriate for testing sprayed concrete are being developed and are referred to in this text. For work outside of Europe, appropriate local standards may be substituted if approved or specified by the Engineer.

G10.1 Test panels and samples

Samples can be taken from either fresh or hardened sprayed mortar/concrete, depending on the property to be measured and its associated test method.

Fresh samples may be extracted from the basic mix, the in situ material or from a test panel. Hardened samples may be cut from the in situ material or from a test panel. It should be appreciated that the properties at each of these locations may be different, due to the spraying process. The most appropriate sample type and location should be used, which will depend on the purpose of the quality control and on the specimens required for the property or properties to be measured.

It is important that panels and samples cut from the panels are carefully labelled and referenced to record all relevant information (such as location and time of spraying, operative name, mix type and orientation) and that they are properly cured as small concrete samples are prone to rapid drying.

G10.2 Compressive strength and density

The compressive strength of sprayed concrete is normally measured by compression testing of cores. Generally, there is no need for special provisions when testing sprayed concrete in compression as there are suitable existing EN test methods.

Fresh concrete from the basic mix in the wet process should be tested in accordance with prEN 12394.

Take, examine and test cores in accordance with prEN 12504 (which refers to prEN 12356, 12390 and 12394), which could be augmented by examination requirements to reflect the nature of sprayed concrete. Core samples can be from in situ (preferred method as most representative) or from test panels.
It should be noted that the prEN 12504 standard has moved away from the use of conversion factors for h/d ratios between 1 and 2 (as given in Table 10.2.1) and states that the preferred h/d ratios should either be 1.0 (for comparison with cube strengths) or 2.0 (for comparison with cylinders strengths). This is because of the difficulty in converting cube and cylindrical specimen strengths due to the complex effects of samples size, h/d ratio, aggregate size and strength level. It is therefore recommended that a decision should be made at the start of a contract as to the type of comparison (i.e. to cube or cylinder strength) and core samples cut to the appropriate length for an h/d of 1.0 or 2.0 respectively. Note that relatively thin layers may restrict choice to a cube comparison, depending on the choice of preferred core diameter. It may be desirable in some circumstances to allow sawn specimens that meet the requirements of prEN 12356.

Early compressive strengths (30 min to 12 hours) are frequently specified in tunnelling and mining applications and in deep excavations in unstable ground. Measurement of early strength is often of interest in accelerated concrete and two methods are used, one a penetration needle test (eg Meyco) for strengths up to 1.0 MPa and the other a bolt-driving test (eg Hilti) for strengths in the range 1-15 MPa. A correlation may be found between the measured penetration or force and compressive strength, although the relationship may be unique to each mix and must be determined during pre-construction testing.

Density should always be measured routinely using the hardened samples for compressive strengths. Cored samples should always be inspected thoroughly to confirm the quality of the application.

G10.3 Flexural strength and residual strength

Sprayed concrete is often subjected to flexural loading in service, and therefore flexural strengths are frequently determined by performing standard beam tests on specimens cut from a test panel. Flexural strength is an indirect measurement of a concrete's tensile strength, as direct measurement of a concrete’s tensile strength is difficult (though a core pull-off test can be used in situ).

Steel fibre reinforced sprayed concrete is usually tested for toughness, in addition to flexural strength. The EFNARC test method covers both properties and the latter is based on a residual strength concept i.e. the post-crack stress and pre-defined values of beam mid-span deflection.

G10.3.1 Testing arrangement

A fibre reinforced prism specimen, sawn from a test panel in accordance with Section 10.1, is subject to a bending moment by the application of load through upper and lower rollers under deflection control to obtain its load/deflection response (the latter exclusive of non-bending deformations). The flexural strength and residual strength class are determined from the load/deflection curve.

The test specimens are sawn prisms, cut from sprayed panels as shown in Figure 10.3.1 and should be prepared to meet the requirements of prEN 12356. The bottom uncut mould face should be identified on the specimen (indicating the direction of spraying). Beams are tested with the bottom uncut moulded face in tension, unless otherwise specified.

Bending deflection, excluding any support deformations and twist, is measured by means of an electronic transducer mounted at mid-span to a yoke that is held to the beam at mid-height of the beam (the neutral axis) and directly over the supports. The testing machine is controlled from the transducer in order to load the specimen at a constant rate of deflection at the mid span of the beam. The load-deflection curve is continuously recorded or logged and where two transducers are used the average mid span deflection can be determined.

G10.3.2 Determination of flexural strength (beam test)

The EFNARC test effectively covers the determination of flexural strength for both plain and fibre reinforced sprayed concretes, using the testing arrangement and procedure for residual strength testing under deflection control. Unlike ASTM C1018, no distinction is made between the so-called 'first crack' and peak flexural strengths. The EFNARC test method identifies a 'first peak' strength (within a 0.1 mm deflection band that limits the maximum value of the first peak load ($P_{0.1}$) in the case of fibre concretes with a large yield plateau). It is assumed that designers will work to this first-peak strength with an appropriate factor of safety, either on the loading (ultimate limit state) or the flexural strength (serviceability limit state at working loads).

In the case of a plain sprayed concrete it may be more appropriate to conduct a test in accordance with the standard method for the modulus of rupture of plain concrete, prEN 12359 Testing Concrete - Determination of flexural strength of test specimens. This method will give flexural strength values that are comparable to other conventionally cast concretes, whereas in the EFNARC test the values are not directly comparable because of the different span/depth ratio and load control which are known to influence the specimen behaviour. It should be noted that the prEN 12359 standard allows sawn specimens that meet tolerances of prEN 12356, but no method stated of achieving this is given and they may be too demanding for sprayed concrete applications.

G10.3.3 Determination of residual strength class (beam test)

The test requires the specimen to be loaded at a constant rate of central bending deflection of the beam, which requires a feedback loop in the control system. It is important that this is adhered to because if crosshead control (as opposed to central deflection control) is used, the machine is able to dissipate stored strain energy into the specimen as it freely cracks and deflects, and so the shape of the load deflection curve is dependent on machine stiffness.

There are five residual strength classes for sprayed concrete which are defined from the shape of the beam stress/deflection curve, and at least two of the three beams must maintain a flexural stress on, or above, the required class boundary up to the deflection limit appropriate to the deformation class and the third must not fall below the next lower class.

G10.4 Energy absorption class (plate test)

The EFNARC specification outlines a plate test designed to determine the absorbed energy from the load/deformation curve as a measure of toughness. The test is designed to model more realistically the biaxial bending that can occur in some applications, particularly rock support. The central point load can also be considered to replicate a rock bolt anchorage. This test has proved to be of considerable benefit and a detailed procedure in given in Annex A.

It is clearly very important that equal support must be applied on each edge. Before placing the plate sample on the test frame, the supports must be levelled out with a cement mortar or plastic layer.

The plate test is appropriate in the pre-construction test programme to check all the parameters affecting the steel fibre reinforced sprayed concrete quality requirements as specified in the project documents. For routine quality control, cube tests to determine strength and wash out tests to check the steel fibre content in-place should be carried out. The plate test is also appropriate for a comparison of different fibre types and dosages and it allows a comparison between mesh-reinforced and fibre-reinforced concretes.

G10.5 Modulus of elasticity

It may be necessary to determine the elastic modulus of sprayed concrete, for instance in rock support design or in repair applications where it is desirable for the repair and substrate to have similar values in order to avoid stress concentration effects.

The test sample must be cut from a test panel of suitable dimensions. The EFNARC specification requires testing to ISO 6784, which is particularly suited to thick layer applications involving coarse mortars or concretes. A smaller prism specimen (160 x 40 x 40 mm) may be appropriate for repair mortars.

It is anticipated that the elastic modulus will normally be evaluated during pre-construction testing, rather than routine quality control. There is a reasonable correlation between compressive strength and elastic modulus, and therefore the former is usually acceptable for routine testing.

G10.6 Bond strength

Routine testing of the bond strength of sprayed concrete is common, due to the dependence of the installation on composite action with the substrate.

Bond strengths for rock support will depend on the local rock condition and must be defined in each case. The test procedure and the bond required must then be agreed locally.

The most common technique is a partial core test in which a tensile load is applied to a steel dolly glued to the end of the core that has been drilled down through the concrete into the substrate below. Several suitable test apparatus are available and CIRIA have published guidance on standard tests for repair materials, including pull-off tests (McLeish, 1993).

The most detailed guidance for pull-off tests is contained in prEN 1542 which is designed for repair but is applicable to other applications. The most crucial aspects of the test are: the avoidance of eccentric loading which will underestimate the bond strength; coring at least 15 mm into the substrate to avoid stress concentrations affecting the bond plane; and careful identification of the failure mode.

When a pull-off test is carried out, three failure modes are possible: failure in the substrate; failure at the bonding surface; and failure in the sprayed concrete layer. Strictly, it is only failure at the bond surface which gives information on bond strength. Unfortunately, reported bond strengths often include the other failure modes (particularly substrate failure), making meaningful comparisons of results problematic.

Bond strength can also be measured in the laboratory from a composite core of sprayed concrete and substrate, as indicated in Figure 10.6.1. This avoids the often difficult environment that occurs with an in situ core pull-off test. Again, the most important part of such a test is ensuring axiality of loading. However, there is no existing or draft detailed method for such a test.

Typical bond strengths for sprayed concrete are in the range 0.5 -2.5 MPa, measured from 60 - 100 mm diameter core pull-off tests. It might be expected that the presence of mesh can reduce the bond of sprayed concrete to a substrate by obstructing the jet of material being shot at the surface and also by allowing the formation of sand pockets behind the bars. There are also reports of reduced bond strength when using high dosages of accelerator, which is not unexpected due to their detrimental effect on other properties including compressive strength.

G10.7 Permeability

There are a variety of tests that produce a measurement of a transport mechanism in concrete, the latter including: absorption by capillary suction, permeation and diffusion. The choice of property and hence test depends on the climate, local environment, the pore structure and its degree of saturation and the likely aggressive actions.

Where the sprayed concrete will be exposed to a high head of pressure (e.g. in a water retaining or underwater structure) it would be appropriate to measure the water permeability. This can be done using a fixed head pressure cell to determine the intrinsic permeability, or coefficient of water permeability, usually by the empirical formula of Darcy. There is no widely accepted standard test method, but many laboratories can conduct such tests on cylindrical core specimens under controlled steady-state conditions and produce reproducible results. An alternative method is prEN 12364, which is based on ISO 7031, referred to in the EFNARC Specification. This test also subjects a cylindrical (including core) specimen to a water pressure (of 500 kPa for 72 h), but measures the maximum depth of penetration as an indirect indicator of water permeability.

In low pressure environments, such as natural atmospheric exposure, it may be more appropriate to measure the capillary suction of the cover zone of sprayed concrete using prEN 13057. In this test slices (at least 20 mm thick) cut from 100 mm diameter cores are conditioned and then the weight gain from immersion of one face in 2 mm of water is monitored over a period of up to 24 hours. From this data the sorption coefficient can be determined (in $kg/mm^2.h^{0.5}$) using an empirical equation that represents a simplified form of the modified Darcy law for non-saturated flow of water.

G10.8 Frost resistance

The favoured EFNARC test is the Swedish standard SS 137244, which is a scaling test that can be conducted with salt solution (3% NaCl) or water. Cube or core samples are sealed in rubber cloth to leave the test surface exposed. The latter is cover by the test solution to a depth of 3 mm which is then put through a 24 hour temperature cycle ranging from 16 - 24ºC to -14 - -20ºC. Scaled material is removed from the sample after 7, 14, 28, 42 and 56 (and sometimes up to 112) cycles, weighed and the frost resistance categorised according to the weight loss (e.g. after 56 cycles: < 0.1 kg/m^2 very good; < 0.5 kg/m^2 good; and < 1.0 kg/m^2 acceptable).

G10.9 Fibre content of sprayed concrete

The EFNARC specification gives considerable details on calculating the fibre content (in kg/m^3) from both hardened and fresh samples. Steel fibres can be extracted from hardened samples, whilst steel, polypropylene or other fibres can be removed from a fresh sample. The methods involve the separate determination of the mass of the fibres and the volume of the concrete sample (including fibres).

A specification could seek to control the fibre content by reference to that of the basic mix (i.e. before spraying). However, this is not recommended because the fibre content in situ is usually significantly less than that before spraying. Also, calculation of an equivalent fibre volume in kg/m^3 is problematic with dry-mix samples.

G11 QUALITY CONTROL

G11.1 General

Tests should be carried out on a routine basis on cores or other samples taken from sprayed concrete applied in the Works. Only for certain specific tests as indicated in the following clauses should panels or beams be prepared for test purposes.
The Site Trials should be repeated if the source or quality of any of the materials or the mix proportions are required to be changed during the course of the Works.
Agreed test should be carried out on a routine basis.

Specimens should be tested in accordance with this Specification: 11.1-3. The tests should be carried out using the following methods:

Test	*Test method*
Compressive strength	This Specification: 10.2
Flexural strength	This Specification: 10.3
Residual strength value	This Specification: 10.3
Bond strength	This Specification: 10.6
Durability/permeability	This Specification: 10.7
Setting time	Appendix 1: 6.3
Fibre content	This Specification: 10.9.3

G11.2 Preconstruction tests

The frequency of carrying out each test for mix control should be in accordance with this Specification: 11.3.1.

G11.3 Quality control

The location of specimens to be taken from the Works should be proposed by the Contractor and approved by the Engineer.

Each core or beam should be marked with an appropriate reference mark and the date and time of spraying.

G12 ENVIRONMENT, HEALTH AND SAFETY

A reduction of the environmental impact and improved occupational health and safety have been among the priority objectives in the further development of sprayed concrete technology. Sprayed concrete with alkali-free accelerating admixtures can offer considerable advantages in terms of both environmental protection and occupational health and safety.

The application of sprayed concrete should meet all health, safety and environment regulations valid at the place of use. Prior to commencement of any contract a full risk assessment and safety plan should be established and approved. For recommended forms to be used refer to Appendix.

G12.1 Safety of personnel

G12.1.1 Dust concentration

During spraying, the building-site crew is at risk due to dust formation and the pollution of the air. The aerosols formed during the sprayed concrete application may constitute a health hazard and therefore have to be minimised. Dust is classified as an aerosol, as are smoke and mist.

Depending on the location and the point in time, the concentration of dust during spraying is subject to major fluctuations, which have to be considered in the interpretation of the results obtained. The fine dust concentration is assessed on the basis of the maximum permissible concentration of contaminants at the work place measured according to the Austrian Guidelines for Sprayed Concrete, Section 12.5.3. Fine dust is defined as dust likely to penetrate into the alveoli of the lungs.

The maximum permissible contaminant concentration at the work place is equal to the maximum permissible concentration of dust which, in general, does not adversely affect the health of workers in the case of repeated and long-term exposure, usually for eight hours, but for no more than 40 hours a week, without use of personal protective equipment (fine-dust masks).

Table 12.2.1 Permissible dust concentration based on maximum permissible contaminant concentration at the work place

Quartz content % by weight	*MAC value c[mg/m^3]*	*Type of dust*	*Nature of dust*
Q < 1	6	fine dust	inert
1 < Q < 3.75	4	fine dust	siliceous
Q > 3.75	0.15	fine quartz dust	siliceous

(Ref.: Austrian Guidelines for Sprayed Concrete, Section 12.5.3)

Given the fact that a range of activities are performed during tunnelling which produce varying amounts of dust, the assessment should be based on the entire working cycle. During spraying, a fine dust concentration of less than twice the relevant maximum permissible contaminant concentration at the work place should be aimed at as an hourly average. If personal protective equipment is used, higher limits are permissible, depending on the protective effect of the equipment. To diminish the dust load over the entire working cycle, the following measures are recommended:

- Dry spraying: use of moist aggregates, machine enclosure, favourable nozzle design, nozzle distance, water content
- Wet spraying with alkali-free accelerators
- Mechanical spraying arms
- Sufficient ventilation

Health hazards for building-site personnel, above all the risk of skin and eye lesions, can be prevented through the elimination of highly alkaline and strongly irritating admixtures, such as aluminate based products or waterglass.

G12.1.2 Personal protection

Personal protection equipment should be always used:

- Helmet
- Goggles, visor
- Dust mask (respirator type - when required, depending on application method and conditions)
- Overalls
- Gloves
- Ear protectors
- Reinforced toe-caps

When applying sprayed concrete overhead, it is not allowed to walk below freshly placed concrete until sufficient strength has been reached. The required time span has to be based on early strength measurements and local conditions (temperature, cement type, dosage/type of sprayed concrete accelerator).

G12.1.3 Precautions in the event of blockages of material lines and nozzle

- Whenever a blockage occurs, the operation of the following equipment has to be interrupted:
  - Main air supply: to be turned off
  - Spraying machine: to be exhausted and/or shut off
  - Accelerator pump: to be shut off
  - Air supply to nozzle: to be shut off
  - Wet spraying machine: take off concrete pressure by reversing the pump.
- Before demounting the line: secure the material lines/nozzle from uncontrolled recoil.
- No personnel in front of the hose under demounting or until the pressure in the material line is relieved.

G12.1.4 Safety of hoses and couplings

- Only special reinforced and approved concrete hoses and couplings should be used. In general they should be approved to a bursting pressure equal to twice the actual working pressure.
- All connections/couplings (of concrete, water, accelerator and air hoses) should be equipped with secondary safety fittings.
- All couplings/hoses should be regularly checked and tested.

G12.2 Environmental issues

Local regulations and standards for environmental issues shall be implemented and followed.
The following environmental impacts should be considered:

G12.2.1 Impact on soil

In the course of spraying, some of the concrete mix drops to the ground as rebound and is removed together with the excavated material.

Given the fact that the rebound mixes with the excavated material and an environmental impact cannot be altogether excluded, a reduction of the rebound ratio is desirable (to less than 25% in conventional traffic tunnels requiring large amounts of sprayed concrete).

G12.2.2 Impact on water

When used in tunnelling, sprayed concrete may be in contact with rock and ground water. Increased leachability of sprayed concrete may therefore lead to segregation and long-term impact on draining water.

Since the leachability of normal concrete is very low even after a short period of hardening, an adverse impact on water quality has not been observed. Thus, concrete qualifies as an environmentally safe construction material. The same applies to sprayed concrete with alkali free accelerators.

The use of accelerators based on alkali aluminate and/or silicates increases the portion of leachable materials in sprayed concrete. The leachability of the rebound is also adversely affected.

Besides the use of alkali-free accelerators, careful working and a low w/c ratio (< 0.5) also contribute towards ensuring a leaching behaviour in sprayed concrete similar to that of normal concrete. The addition of silica fume may likewise have a favourable influence on the leaching behaviour.

G12.2.3 Rebound disposal

Rebound material should be disposed of in accordance with national regulations or requirements specified by the Engineer.

EDITORIAL CORRECTIONS TO SPECIFICATION

6.1 b) Insert ‘of’ after ‘choice’.

6.2 Should be section 5.1.2.6 not Section 5.5

6.3 Should be: “The alkali content of the CONCRETE shall...”

6.4 line 2: Should be Section 4 not Section 5.

GUIDELINES TO APPENDIX 1: ADMIXTURES FOR SPRAYED CONCRETE

GA1 Scope

Appendix 1 deals only with tests and requirements for special admixtures used in sprayed concrete and which are not specified in any other EN standard. The objective of the tests is to obtain a general approval of the tested products for use in sprayed concrete. All tests and requirements are described for laboratory conditions and have nothing to do with requirements for Works or Works Tests.

GA3.2 Sprayed concrete admixture

Sprayed concrete admixtures can be (and normally are) dosed in different dosing ranges than standard concrete admixtures. Sprayed concrete admixtures can either be in liquid or in powder form.

GA3.3 Sprayed concrete accelerating admixture

Sprayed concrete accelerating admixtures provide a very early set acceleration and/or a very early hardening of the concrete beyond the limits of conventional concrete admixtures. In addition to this, they enable the build-up of layer thicknesses - on vertical surfaces as well as overhead - which without the use of these admixtures are otherwise not possible.

Set accelerating sprayed concrete admixtures cannot be compared in performance or requirements with conventional hardening accelerators used for normal concrete.

Among the sprayed concrete accelerating admixtures different types can be identified which vary in performance, dosing method and dosing rate. Most common in use are liquid products.

The most commonly used types of sprayed concrete set accelerating admixtures are:
- Sodium aluminate
- Potassium aluminate
- Silicates
- Modified silicates
- Alkali-free products
- Other special set accelerating sprayed concrete admixtures.

NOTE: Sprayed concrete accelerating admixtures should be chloride-free.

GA3.4 Thixotropic admixture

A thixotropic sprayed concrete admixture can be a single product or consist of several products interacting with each other. The admixture or admixture system is added to the sprayed concrete mix in order to provide thicker layer thicknesses (50-100 mm) - on vertical surfaces as well as overhead - than with sprayed concrete mixes without any admixtures or without set accelerating admixtures, without sagging or drop-off.

GA3.5 Hydration control admixture

The hydration control system facilitates the storage and handling of a sprayed concrete mix well beyond the limits of conventional concrete storage times (1-2 hours), without adversely affecting the hydration. The addition of the first component prevents pre-hydration. When the second component, which can be a conventional accelerator, is added, the concrete is re-activated and the setting performance is equal to that of freshly batched concrete.

Hydration control admixtures can be used both for wet-mix and dry-mix spraying.

GA3.6 Bond improver

Special admixture added to the basic mix of the sprayed concrete or at the nozzle to improve the bond between the sprayed concrete layers and/or the tensile bond of the substrate surface of the sprayed concrete.

Bond improvers do not adversely affect the bond between layers and require no special precautions in terms of cleaning/removal.

Some bond improvers can also work as a replacement for external curing. These so called internal curing admixtures reduce shrinkage and crack formation, improve the degree of hydration and enhance the permeability and the sulphate and frost resistance of sprayed concrete.

Preconstruction tests should be carried out to confirm the results. The manufacturer's instructions regarding dosage rate etc. should be followed.

GA3.9 Compliance dosages

Hydraulic binder not only means cement, but also includes silica fume, pfa and ggbs (refer to Specification, 4.7 and table 5.3.1).

However, the K factor (binding capacity) is not the same for all hydraulic binders and must therefore be considered for the calculation of the dosage of sprayed concrete admixtures:

Binder	*K factor*
Cement	1
Silica fume	2 (dosage <8%); 1 (dosage 8-15%)
Pfa	0.5
GGBS	0.5

Example:

Mix design with cement, pfa and silica fume: per m^3: accelerator dosage, 5%

300 kg of cement (K factor: 1)	=	15.0 kg of accelerator
100 kg of pfa (K factor: 0.5)	=	2.5 kg of accelerator
20 kg of silica fume (K factor: 2)	=	2.0 kg of accelerator

This results in a total accelerator dosage of 19.5 kg/m^3 of sprayed concrete mix.

GA4 Requirements

These requirements are for the purpose of product approvals and are only related to testing in the laboratory, under strictly defined conditions.

GA5.1.2 Reference aggregates

Oven-dried aggregate should preferably be used.

GA5.5.2.2 Spraying process of control mix panel, and
GA5.5.2.3 Spraying process of test mix panel

No mould should be sprayed in an overhead position. Only horizontal spraying (control mix panel) and vertical spraying (test mix panel) are allowed.

GA6.3.2.2 Preparation of reference cement paste

The method is a modified version of EN 480-2 (refer to Appendix 1, 6.3.2 - 6.3.2.4).
Particular attention should be paid to the following steps in the procedure:

- the cement is added before the water.
- shorter mixing times after the addition of the sprayed concrete accelerating admixture; maximum of 15-30 s. Too long or inaccurate mixing times will result in incorrect setting times.

ANNEX A
Sprayed concrete – Determination of energy absorption capacity of slab specimens.

(references to Figures are those in the Specification)

1 SCOPE

This specification relates to a method for the determination of the load/deflection response of a slab specimen in order to calculate the energy absorption capacity up to a specified deflection.

2 PRINCIPLE

A sprayed slab specimen is subject to a load, under deflection control, through a rigid punch positioned at the centre of the slab.

The load-deflection curve is recorded and the test is continued until a deflection of 30 mm is achieved at the centre point of the slab.

From the load-deflection curve a second curve is derived giving the absorbed energy as a function of the slab deflection.

3 APPARATUS

3.1 Test equipment

The test shall be carried out using a testing machine conforming to 4.2 and 4.3 of EN 12390. The stiffness and control system of the testing machine shall be such that the test can be deflection controlled.

A calibrated electronic transducer.

An electronic data logger or XY plotter.

3.2 Application of the load

The device for applying the load shall consist of:

- a frame with a rigid square support 100 mm wide and 500 mm internal side supporting the slab
- a rigid steel square block for loading having a contact surface of 100 mm x 100 mm and thickness of 20 mm, positioned at the centre of the upper face of the slab (fig. 10.4.1);
- a suitable mortar bedding material to be applied between the square support and the sample and between the sample and the loading block.

3.3 Deflection measurement and control

Bending deflection shall be measured by means of an electronic transducer, excluding any support deformation.

The testing machine shall be controlled from the transducer in order to load the slab at a constant rate of deflection at its centre.

4 TEST SPECIMEN

4.1 A square specimen shall be sprayed and cured in a mould with a side of 600 mm and trimmed to a thickness of 100 mm (-0,+10 mm) immediately after spraying.

4.2 The prepared slab shall be stored under water for a minimum of 3 days before testing and kept moist during testing.

4.3 Testing shall be performed at 28 days, unless otherwise specified.

4.4 The specimens shall be examined before and after test and any abnormalities shall be reported.

5 PROCEDURES

5.1 Preparation and positioning of specimens

The load shall be applied perpendicularly to the sprayed face; the smooth cast side of the test slab being on the bottom during the test.

The smooth face shall be bedded securely with a suitable mortar bedding at the contact with the supporting frame. Also the loading block shall be bedded onto the slab ensuring that it is perpendicular to the applied load.

5.2 Loading

The testing machine shall be controlled from the transducer in order to load the specimen at a constant rate of deflection of 1 mm per minute at the centre of the slab.

The load and deflection shall be continuously recorded with the data logger or XY plotter until a deflection of at least 30 mm is obtained (fig. 10.4.2).

The loading shall be stopped when the central deflection exceeds 30 mm.

6 EXPRESSION OF RESULTS

From the load-deflection curve a second curve shall be derived giving the absorbed energy as a function of the slab deformation (fig. 10.4.3)

The absorbed energy (in Joules) corresponding to the area under the load-deflection curve between 0 and 25 mm deflection shall be determined.

7 TEST REPORT

The test report shall include:

- identification of the test specimen
- average thickness of the slab, evaluated to within 10 mm, at the location of the punch section
- type and stiffness of the testing machine
- curing conditions and age at testing
- load-deflection curve
- calculated energy-deflection diagram
- energy absorption for 25 mm deflection; expressed to nearest 10 Joules