

PERMANENT SPRAYED CONCRETE LININGS

ITA Working Group n°12 and ITAtech

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INTERNATIONAL TUNNELLING
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The International Tunnelling and Underground Space Association/Association Internationale des Tunnels et de l'Espace Souterrain (ITA/AITES) publishes this report to, in accordance with its statutes, facilitate the exchange of information, in order: to encourage planning of the subsurface for the benefit of the public, environment and sustainable development to promote advances in planning, design, construction, maintenance and safety of tunnels and underground space, by bringing together information thereon and by studying questions related thereto. This report has been prepared by professionals with expertise within the actual subjects. The opinions and statements are based on sources believed to be reliable and in good faith. However, ITA/AITES accepts no responsibility or liability whatsoever with regard to the material published in this report. This material is: information of a general nature only which is not intended to address the specific circumstances of any particular individual or entity; not necessarily comprehensive, complete, accurate or up to date; This material is not professional or legal advice (if you need specific advice, you should always consult a suitably qualified professional).

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AUTHORS : Wolfgang Aldrian, Alun Thomas, Nick Chittenden, Karl Gunnar Holter

CONTRIBUTORS : Yves Boissonnas, Catherine Larive, Tomislav Rogan, Davide Michelis

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ACI : American Concrete Institute

CEN : Comité Européen de Normalisation (European Committee for Standardisation)

DSL : Double Shell Lining

EFNARC : European Federation of National Associations Representing producers and applicators of specialist building products for Concrete

EN : European Standards

F_{max-el} : Maximum load in the elastic zone of a residual flexural tensile strength test

FRC : Fibre reinforced concrete

FRS / FRSC : Fibre reinforced sprayed concrete

GFRP : Glass Fibre Reinforced Plastic

ITA-AITES : International Tunnelling and Underground Space Association

ITAttech : Prime Sponsor-led technical committee within ITA-AITES

OBV : Österreichischer Beton Verein, Austria

OVBB : Österreichische Vereinigung für Beton- und Bautechnik, Austria

PSCL : Permanent Sprayed Concrete Lining(s)

RCS : Respirable crystalline silica

SCL : Sprayed concrete lining(s) – also known as shotcrete linings

STUVA : Studiengesellschaft für Tunnel und Verkehrsanlagen (Research Association for Underground Transportation Facilities), Germany

UCS : Unconfined Compressive Strength

WG : Working Group (part of the ITA activities)

Base mix design : The mix composed by cement, aggregates, admixtures, water (and fibres if applicable) as it is poured in the hopper of spraying equipment

Early-age sprayed concrete : Sprayed concrete younger than 24 hours old after spraying.

Hard rock : Massive, strong rocks which behave as a continuous mass, typically with a UCS > 50 MPa.

Hardened sprayed concrete : Sprayed concrete aged with more than 24 hours old after spraying.

Reference sprayed concrete : The “base mix design” sprayed with accelerator from the nozzle. This becomes the reference for testing purposes.

Soft ground : Soil or weak rock which generally behaves as a single, continuous mass, typically, with a UCS < 10 MPa.

Weak rock : Rock mass with lower in-situ strength properties than hard rock. The term covers several types from moderately strong, jointed rock which generally behaves as a collection of discrete blocks, to moderately strong rock mass composed of low strength rock, to highly fractured or laminated rock mass, sometimes with anisotropic behaviour.

The main objective of this guideline is to give infrastructure owners and their advisors the confidence to incorporate permanent sprayed concrete linings (PSCL) into their underground space design. In line with the objectives of the ITA Statutes this document aims to encourage the use of tunnels and underground space for the benefit of the public, the environment and sustainable development and to promote advances in tunnelling through the provision of information.

This guideline will share state-of-the-art expertise on PSCL to encourage wider acceptance of this tried-and-tested solution. PSCL can be used for primary linings, secondary linings or both. Using PSCLs can lead to lower capital costs, operational costs and carbon footprints when compared to traditional lining solutions. Wider adoption of PSCLs will have a positive impact on the sustainability of underground spaces and increase their viability and potential uses.

PSCL has already been used in underground works throughout the world in a wide variety of ground conditions (see case studies in chapter 15 (Appendix). By 2017, over 1500 km of PSCL had been built in hundreds of projects. Its use is well established in many northern European countries and Australia. In other parts of the world, its acceptance amongst clients and their advisors has been more limited for a number of reasons, despite comparable ground conditions. This can either be because there are no relevant national standards or because local design practice does not favour PSCL, even when standards exist.

This document is not intended to be a comprehensive design guide or construction specification. Instead it aims to inspire and inform so that more projects can take advantage of this technology. It focuses on wet sprayed concrete and machine application since PSCL is almost always applied in this way.

This document is specific to PSCL and does not discuss routine construction practices. It does not replace the need for expert advice

during planning, design or construction, but should give project teams a resource for understanding the key risks and issues and how to manage them. The approaches proposed here can be adapted to a specific project to suit the parties involved and the details of each scheme.

4 >> WHAT IS PERMANENT SPRAYED CONCRETE ?

Sprayed concrete contains the same basic raw materials as conventional concrete with an added accelerator¹ to speed up hydration. By definition it is applied by spraying. PSCL generally has the same components as temporary sprayed concrete and is applied in the same way. However, unlike temporary sprayed concrete, PSCL must have the same service lifetime as the tunnel or underground facility to which it is applied.

Over the past 15 years, there have been significant developments in spraying as a technique for placing concrete. Improvements to materials, equipment, testing and quality assurance processes have allowed sprayed concrete to become a cost-effective solution which has the same durability as conventionally-placed concrete.

From a design perspective, the performance of the material in a PSCL is critical from the moment it is applied until the end of its service life. This requires the designer to consider both long-term and short-term load cases together with all the intermediate conditions which may occur during the construction of the lining system.

For the long-term case, a PSCL should be considered in the same way as any other permanent concrete structure. Hence, codes such as Eurocode 2 (EN 1992-1-1 (2004)), and ACI 318 (ACI 2019), should be applied to determine normal loading conditions.

For short term considerations, the commonly-used codes may not be entirely applicable, since they are written for structures where concrete is loaded at later ages.

Because it is permanent, the choice of reinforcement for PSCL is important and

may differ from the reinforcement used in a temporary sprayed concrete. There have been problems in the past with the corrosion of steel mesh or lattice girders in sprayed concrete. To overcome these durability concerns, structural fibres – either macrosynthetic or steel – are often used in PSCL instead of steel reinforcing bars.

¹ Most sprayed concrete uses an accelerator but, in some cases, it has been applied at high velocity with no accelerator instead.

5 >> TYPICAL APPLICATIONS AND CONSIDERATIONS

5.1 INTRODUCTION

Sprayed concrete has many applications. The most common is for ground support in tunnels and slopes. The first recorded sprayed concrete use in tunnels (as gunite, later named torcrete or shotcrete) was around 1920 in Swiss water Tunnels (Kovari 2002). From the 1970s, its use in rock became more frequent, and since the early 1980s Scandinavian countries have used it extensively. In soft ground, PSCL has gained popularity since the early 1990s.

PSCL is particularly well suited to short or irregular-shaped tunnels with many junctions, such as those typically required by underground urban rail projects. The Crossrail project in London is one excellent example where PSCL was chosen as the best solution for the mined stations² in soft ground. When combined with spray-applied waterproofing membranes, PSCL offers opportunities to optimise the size and shape of the tunnels, beyond the advantages offered by conventional SCL techniques.

In 2001 Working Group 12 of the ITA-AITES published a compilation of 150 cases from 11 countries with successful use of PSCL (Franzen et al., 2001). Meanwhile this Working Group has gathered information up to 2015. In this period sprayed concrete has been used on an increasing scale for permanent purposes, where some few selected reference projects are shown in Appendix 1.

Figure 1 illustrates the type of projects where PSCL has been used and Figure 2 shows the geographical spread of PSCL.

² NB: At Farringdon the primary lining is PSCL but inside there is a sheet membrane and a cast insitu secondary lining for specific geological reasons.

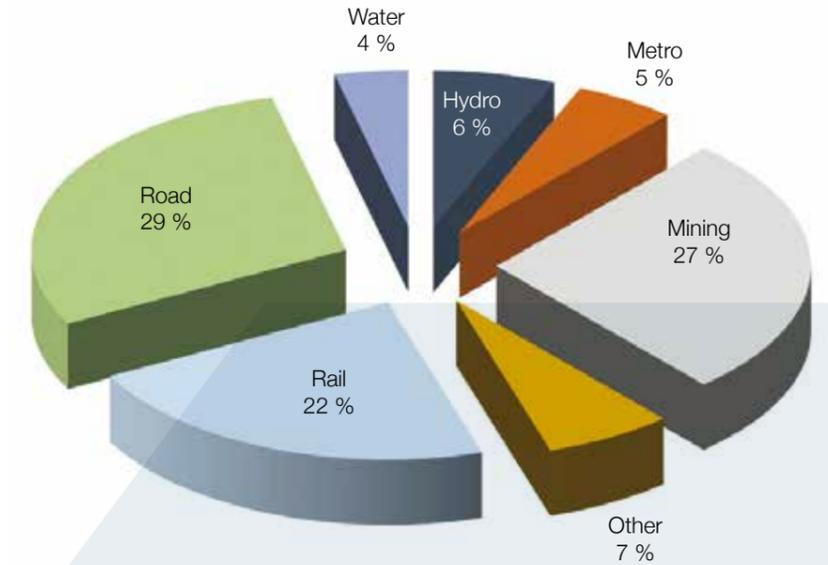


Figure 1: Distribution of PSCL Tunnels by sector (ITA-AITES, internal data compilation)

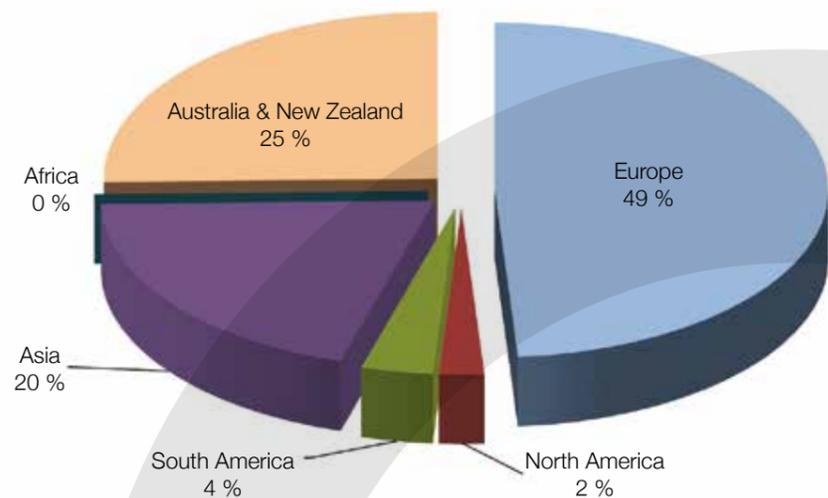


Figure 2 : Distribution of PSCL tunnels by location (ITA-AITES, internal data compilation)

5.2 SPRAYED CONCRETE VS. CAST CONCRETE SUPPORT

Currently cast in-situ secondary concrete linings and precast concrete segmental linings are more commonly used for final inner linings than PSCL. Though all are concrete, the mix designs are different. PSCL contains a higher quantity of cement than cast concrete, uses smaller aggregates and contains accelerators to make it stick to the substrate. These differences may influence some of the concrete-specific properties like durability, shrinkage and creep.

The main differences between PSCL and cast concrete are:

- How it is placed – by spraying.
- When it is loaded.
- The characteristics of the final structure.

The way that PSCL is placed and its final characteristics are very much linked. The right equipment and competent people must be used to apply PSCL. See chapters 10, 12, 16 (Appendix 2) and 17 (Appendix 3).

The characteristics of the final structure cover its material properties, life span of the structure (see chapter 7), surface finish and aesthetics. A certain roughness and unevenness are typical unless special additional measures, such as screeding or float-finish are employed, if a smoother surface finish is required.

With respect to loading, it is often said that sprayed concrete is loaded immediately after being placed. But this is only true in soft ground/weak rock, where the sprayed concrete is the primary support.

Sprayed concrete placed onto a freshly-excavated substrate in a soft ground or weak rock tunnel will usually experience ground loads immediately after being placed. Its load-bearing capacity depends very much on how the strength and stiffness of the sprayed concrete develops. The loading comes from ground movement, which is heavily influenced by the excavation details. Additionally, the sprayed concrete must carry its own weight since there is no shutter to support its weight.

PSCL in soft ground or weak rock needs special treatment because the primary concrete shell is loaded immediately. The loads should be calculated using material properties and excavation sequences that reflect reality. While primary layers of PSCL may take much of the early-age loading from the ground, subsequent layers will be loaded more slowly and to a lesser extent in the early ages. PSCL as “composite lining” must therefore consider the timely sequence of application of primary and final inner lining, the load transfer from outer to inner layer, also due to creep, and the change with time of sectional forces in the two sprayed concrete layers (Aldrian W. 1991; Golser J. and Kienberger G. 1997). There is also evidence that the simpler calculations used in most designs (i.e. assuming linear elastic behaviour for the lining) tend to over-estimate the loading in the lining (Thomas 2019).

Where the sprayed lining is loaded early, there is a risk that its integrity can be damaged. This occurs if sprayed concrete is loaded to more than 70% of its current strength at an early age and this situation persists (Thomas 2019). However, if the lining is designed as part of the permanent works, safety factors in design codes will ensure that the loading is kept well below this level in the permanent case.

If the loading exceeds the strength build-up of the sprayed concrete, local shell failures may occur, visible as cracks or shear planes or both. In such cases, the full primary lining thickness of sprayed concrete should not be considered as an integral and durable part of the final lining design.

In contrast, sprayed concrete placed as ground support onto a hard rock substrate in a drill and blast excavation, is likely to experience little or no loading from ground or rock deformation and movement. It must only carry its own weight. This means that most of the sprayed concrete will remain unloaded. However, local loads can occur immediately in spots where rock fragments and blocks are kept in place by the sprayed concrete, so there is still a requirement for the early age strength.

Sprayed concrete applied as a final inner lining is normally placed when the main ground deformations have stabilised, according to NATM philosophy (OVBB, 2006). Therefore, a sprayed concrete inner lining will not immediately be loaded from ground deformations. Loading may gradually happen over a longer time period due to degradation of temporary elements of the primary support or time-dependent deformation, such as creep, squeezing, swelling and consolidation. Also, water pressure may build up over time, very much depending on the design concepts employed. When the primary sprayed concrete lining can meet the requirements for long term durability, the entire SCL structure; primary lining and final inner lining will constitute the complete permanent lining structure.

In summary, standard design approaches can be used for PSCL in most underground structures, since the concrete is already hardened before it is loaded.

5.3 RANGE OF APPLICATION OF PSCL

There are few cases where PSCL is not a viable technical solution. Alternatives should be considered where the initial primary support of sprayed concrete suffers damage that might impair its ability to meet durability requirements. Examples of this include squeezing ground, rock burst, very active water ingress that disrupts the concrete when it is sprayed, heavy blasting at an early age or tunnels with very aggressive groundwater chemistry.

From an economic point of view, in soft ground, PSCL is best suited to shorter tunnels (less than 1km), particularly if there is a variable cross-section or lots of junctions (see also the case studies in chapter 15 (Appendix 1)). PSCL has been used for long tunnels in rock, such as the Vereina tunnel in Switzerland and the Lærdal road tunnel in Norway.

6.1 STRUCTURAL CAPACITY

The structural capacity of sprayed concrete has increased as technology has developed. This, in turn, has broadened the scope of its application. Sprayed concrete was introduced as gunite at the beginning of the 20th century and has been used as temporary rock support in tunnels more widely since the mid-1950s. From the 1970s, when wet sprayed concrete was introduced, the quality of sprayed concrete began to improve but the design requirements remained rather low. Today, a typical strength requirement at 28 days for PSCL is C25/30 (OBV 2013) or greater. Project-specific requirements may lead to even higher strengths.

The analysis and design of any lining system is complex and requires experience and common sense. The designer needs to understand material properties and behaviour as well as the ground conditions and the construction methodology. If simple linear elastic methods of analysis are adopted, together with a stiffness value for the concrete taken from standard structural codes, then an over-prediction of stress will almost certainly occur (Thomas 2019).

The stresses and strains that the lining will experience are complex. The designer must take a range of factors into account such as :

- Strength and stiffness of the sprayed concrete with respect to time (from, say, 15 minutes to 120 years).
- Load cases, which depend on ground conditions, hazards, and method of construction including advance rates for primary support layers and operation.
- Potential creep and relaxation of the concrete, shrinkage and thermal effects.
- Other load cases such as fire.

6.2 SOFT GROUND TUNNELS VS. ROCK TUNNELS

The design considerations for PSCL in soft ground or hard rock are different. This is due to the differences in how it is loaded and hence differences in required strengths, geometry and construction sequences.

6.2.1 Loading

Sprayed concrete linings in soft ground tend to be quite uniformly loaded by the ground, hence the bending in the lining is usually quite limited. However, there can be cases where significant bending occurs such as at junctions or due to isolated, asymmetric loading from blocks (see also 6.3). Additionally, the sprayed concrete lining also prevents the ground from weathering or changing its cohesion by drying out.

Tunnels and underground structures excavated in hard rock often need very little support. The sprayed concrete is partly a safety measure to ensure the long-term integrity of the underground opening. It also protects the rock from weathering and prevents small pieces of rock or wedges from falling down. These sprayed concrete layers are typically only locally loaded, and the loading tends to be low, as the arching effect in the rock guarantees the stability. Where the PSCL is used with other temporary support measures such as spiles or temporary rock bolts, the lining will have to take over the asymmetric load from rock wedges as the temporary support degrades over time.

The relative stiffness of the PSCL is different in soft ground compared to hard rock. In soft ground tunnels, the sprayed concrete lining tends to be significantly stronger and stiffer than the soft ground.

In hard rock environments, the opposite is true. This relative stiffness therefore plays a role in determining the loads on the lining. This is also the case in jointed hard rock, where the high rock mass stiffness results in a largely unloaded lining, but local loads might be caused by blocks. The empirically based Q-system has proven successful as a design tool for rock support under such conditions.

6.2.2 Geometry

The shape of the lining is important in soft ground because it needs real support. The sprayed concrete must be of high and reliable quality and the geometry should support the stress redistributions around

the opening, as well as the loading due to the sprayed concrete itself. Stresses will be due to normal forces (compression) and small bending moments, hence rounded geometries are preferable.

In hard rock a favourably rounded excavation shape will be an advantage but is not critical.

6.2.3 Construction sequences

These vary between soft ground and hard rock. In soft ground tunnels, the advance length is around 1 metre or a little more. The excavation cross-section is often divided into stages such as top-heading, bench and invert to ensure the stability of the excavation face. The placed sprayed concrete thicknesses are around 150 to 300 mm, depending on the excavated geometry, and the concrete is sprayed immediately after the face has been opened.

In hard rock excavations, blast rounds can be several meters long, with the total thickness of sprayed support often achieved at a certain distance behind the face, because of optimization of rock support works. The total layer thicknesses of the primary sprayed concrete tend to be between 80 and 150 mm.

6.2.4 Secondary linings

For long term stability soft ground tunnels usually require a secondary lining, sprayed or cast, whereas hard rock tunnels do not necessarily need one. In soft ground tunnels, it is usual to apply the secondary lining in the rear zone of the tunnel excavation, often quite a long time after the primary lining has been applied. Normally all deformations in the primary lining must level off before the final layer is placed. The design will define the earliest and the latest time and distance behind the heading when the full lining can be applied.

The secondary layer can be sprayed concrete, rather than cast. The thickness will vary, depending on design considerations. If the primary and secondary layers are considered to be bonded and the initial layer can be considered permanent, the two

layers can share the load and the secondary layer can be thinner than a cast secondary layer. If bonding is ignored, the secondary lining will be of a similar thickness to a cast secondary lining.

For hard rock tunnels, if additional support is needed, then the secondary sprayed concrete lining can be applied at a later stage. The distance to the face is not important.

6.2.5 Concrete placement

The differences between PSCL for soft ground and hard rock have implications for the characteristics of the sprayed concrete and the way it is placed. In soft ground, it is likely that the sprayed concrete will be placed in a confined space, over small areas, and it will be immediately loaded. To address these issues, the mix design should cater for all the site-specific variations that will occur, with a strength development that allows the required thicknesses to be placed without problems. A qualified operator (nozzleman), who is aware of what they are doing is essential.

For PSCL applied in hard rock or as a secondary lining, there is more flexibility as to when the sprayed concrete can be placed. This reduces the spray joints which occur when equipment is moved.

6.2.6 Crack control and construction joints

Since sprayed layers in soft ground experience loading immediately, shrinkage cracks occurring over time will be negligible, but attention must be paid to all construction joints, especially the horizontal joints, to ensure the structural long-term load bearing capacity. The vertical joints are prone to attract water, which needs to be dealt with separately. The freshly placed concrete must never be over-loaded, as this would produce micro-cracks which would reduce the long-term load bearing capacity.

Since sprayed concrete in hard rock or as secondary sprayed concrete lining is not loaded immediately, it will not be in

compression at the beginning, so more attention must be paid to potential thermal and shrinkage cracks, the watertightness of the sprayed concrete (spray applied waterproofing membranes can be considered), the surface appearance and the aesthetics. The mix design must focus on reducing the potential cracking of unloaded or very lightly loaded layers.

6.2.7 Neither soft ground nor hard rock

There are cases, such as weak rock, that fall between soft ground and hard rock. Empirical design methods, such as the Q-system and RMR should only be used with great care under such conditions, since they tend to generalize the geomechanical assessment. There it is recommended to properly review the failure mechanisms and to apply another type of design method.

6.3 LONG-TERM STABILITY, CREEP AND RELAXATION AS WELL AS SPECIAL LOAD CASES

Durability is discussed in chapter 7. Specific concerns typically centre on the stability of the components of hydration, which are the products produced when cement reacts with water and which bind the aggregates in concrete together. It is widely believed that the latest additives and accelerators do not have any detrimental effects on sprayed concrete over the long term (see also Hagelia 2018). Research to date suggests that the products of hydration in accelerated sprayed concrete are like those in a conventional durable concrete (BASF 2012, Thomas 2019).

All concrete creeps and, in general, this is dealt with in design standards for reinforced concrete. The principles are the same for sprayed concrete. Sprayed concrete can exhibit a higher potential for creep and relaxation (which is a lowering in stress due to creep), for a variety of reasons, in both compression and tension (Thomas 2019). The majority of the load on the lining comes from ground deformation and, once the deformation stops, the stresses in the lining may reduce due to relaxation (Aldrian

1991, Golser and Kienberger 1997). In the past in tunnels, this effect has been cited as a benefit because it can reduce stress concentrations and close cracks in permanent linings. The magnitude of the creep and relaxation depends on many factors such as age of concrete, mix design, the type of fibres in the concrete, the intensity of loading and its duration, as well as exposure to temperature and humidity fluctuations (Thomas 2019).

Fibre reinforced sprayed concrete (FRSC) with macrosynthetic fibres tends to exhibit more creep potential than FRSC with steel fibres in tension. However, most linings will exhibit creep in compression which is not related to the fibre type. The design must consider the relevance and impact of creep in the context of the interaction between ground and structure, for each case individually. For example, in the case of lightly loaded, shallow tunnels in soft ground, creep may not be significant in reducing loads or creating a risk of unacceptable deformations (Thomas 2019). Tensile creep is normally not an issue as most linings remain under compression in service. However, if the structural analysis yields that tensile creep might become an issue for the lining in service, then appropriate testing should be conducted to understand the response of FRSC to sustained flexural load (e.g. Larive et al. 2015).

Fire protection and loading post-fire must be considered for PSCL. Concrete can spall at temperatures as low as 400 degrees Celsius when exposed to high-density fires. The high temperatures possible in a tunnel fire can cause catastrophic spalling. Typically, micro polymer fibres are added to improve the fire resistance of the lining (Winterberg & Dietze, 2004). These fibres greatly reduce the risk of explosive spalling. As an alternative, thermal insulation can be used, either by applying a fire protection mortar or special sprayed concrete mixes. However, a lining may still need some repair work after a major fire. The capacity of the lining exposed to a fire can be checked in the same way as conventional cast concrete.

In other special load cases, such as seismic loading, swelling, surge pressures, aerodynamic loads or fixings, PSCL can be treated in the same manner as any other lining type and with the same design methods applied.

In drill and blast tunnels, PSCL is also subjected to blast vibrations at an early age. Studies have shown that in typical cases, the concrete is likely to experience relatively low vibration velocities (between 0.5 and 1.0 m/s) which should not cause damage (Ahmed 2012). Ansell (2004) provided more detailed guidance on ages at which a certain thickness of plain sprayed concrete could withstand different sized blasts at different distances.

6.4 SHRINKAGE DUE TO THERMAL EFFECTS

A good bond between the ground and the concrete or between primary and secondary layers of concrete is important (see 6.5). But the bond also acts as a restraint on the concrete which can lead to cracking if the concrete cools down too quickly.

A similar phenomenon was first observed in the cast concrete linings of large tunnels in Germany in the 1980s and described by Springenschmid (1986). Distinctive patterns of cracking appeared repeatedly, which engineers realised were related to thermal shrinkage.

Comparable patterns have partly appeared in sprayed concrete linings, in situations where the lining is not under compression (which closes the cracks up). This could be in a hard rock tunnel, in areas where there is little or no loading, or in soft ground where an inner lining is taking little or no load due to the primary lining being oversized and hence carrying all the load.

When a sprayed concrete is applied to the wall, it gains heat due to the hydration process. The still-soft concrete cannot expand longitudinally or circumferentially as it is surrounded by more concrete trying to do the same, and hardy builds up any

compression, due to its relative softness. Before it starts to cool, it has already gained some strength. As there are no compressive forces in the lining, the temperature reduction and subsequent contraction immediately leads to tension.

The bond between sprayed concrete and substrate resists this contraction, which creates tensile forces in the hardening concrete. The tensile (and compressive) strength of concrete only develops over time. If the concrete cools at a rate that is too fast, the tension will be developed faster than the tensile strength, and cracking will occur.

To reduce the risk of this cracking occurring, the difference between the peak temperature and the final temperature of the concrete in operation must be minimised. Hence, all factors creating unnecessary heat during hydration need to be eliminated. This means limiting the fresh concrete temperature – for example, to a maximum of 22°C, according to the Austrian Guideline on Inner Shell Concrete (OVBB 2006), minimising cement in the mix design to limit the associated heat development, temperature control in the tunnel, considering spraying during night or, if necessary, spraying during cooler seasons.

The addition of accelerators to the sprayed concrete mix starts the hardening process and the heat develops faster than for cast concrete. For primary linings, the strength gain of the sprayed concrete should match the J- curves, typically J2 (Austrian Guideline Sprayed Concrete (OBV 2013), EN 14487-1 Sprayed Concrete (2006)), where early-age strength is specified. However, there are no such guidelines for the sprayed inner concrete shell.

Optimising the accelerator means adding just enough to allow a proper build-up of layers, but not enough to create excessive heat development. The strength criteria for an inner lining are the final strength values, specified for 28 or better 56 days.

Additionally, drying out and cooling down of the freshly applied layer can be slowed

down through special measures like proper curing, for instance through water or water mist, internal curing admixtures, and clever ventilation (e.g. shielding the freshly applied layer from air flow). All these measures allow the sprayed concrete to gain some tensile strength before cooling to the critical temperature.

The Austrian Guideline on Inner Shell Concrete (2006) recommends that the total amount of water in the mix should be limited. For 'cast concrete and structures with special properties', this is limited to a maximum of 170l/m³, which also limits the maximum cement content due to the water-binder ratio (most standards set the limit to max. 0,5). The total cement and binder content should be just enough to reach the desired properties, without overshooting strength values.

Adding air entraining admixtures, which is commonly done to improve freeze-thaw resistance, can also help by producing less stiff concrete. Additionally, it also assists in stopping cracks propagating through the structure (Springenschmid 1986).

Section 9.3 summarizes how these factors impact on mix design.

All this needs to be incorporated in the design specifications. The potential impact of cracks on the functionality and durability of the structure has to be checked for each individual case, since visible cracks may often present an aesthetic challenge only.

6.5 BONDING

Unlike cast concrete, sprayed concrete bonds to the substrate, which may be the ground, concrete or a double-bonded waterproofing membrane between sprayed concrete layers. The strength of the bond with the ground varies, depending on its geological properties such as surface roughness and the rock strength. Typically, values can vary from 0.5 to 2.5 MPa, depending on the substrate (Thomas 2019). The strength of the bond increases with increasing age.

In hard rock, a good bond strength is vital because the sprayed concrete must be able to contain small key blocks falling or to resist very local shear displacement. In soft ground, the ability to bond layers of sprayed concrete together is essential for the lining to function as a monolithic structure. This also eliminates potential water paths. Typically, the bond for the mature concrete should be greater than 0.5 MPa. Section 10.4 contains practical guidance on how to achieve a good bond.

The bond also influences the potential crack pattern, as it constrains free movement. For thin layers of sprayed concrete, the bond needs to be high enough to avoid debonding due to tension induced by shrinkage.

6.6 WATERTIGHTNESS

The watertightness required for each tunnel depends on its use and other requirements which are defined in the design phase. The STUVA and the ITA-AITES have provided guidance on this (see Table 1). The required level of watertightness can be achieved in several ways, depending on factors such as the permeability of the ground and the water pressure.

Several technical solutions are available for waterproofing. PSCL is not synonymous with spray applied waterproofing membranes but the two technologies can work well together because of the bonded nature of the membranes and the compatibility of the two materials (Holter, 2015). More information on

Class	Type	Moisture Characteristics	Definition (BTS 2010)	PERMITTED LEAKAGE AND REFERENCE LENGTH	
				l/m ² .day over 10 m	l/m ² .day over 100 m
1	Working rooms	Completely dry	No damp areas visible on the tunnel lining	0.02	0.01
2	Station tunnel	Substantially dry	Occasional damp patches which do not discolour blotting paper	0.10	0.05
3	Rail tunnel	Capillary wetting	Occasional damp patches but no drops of water	0.20	0.10
4	Utility tunnel	Weak trickling water	Occasional drops of water	0.50	0.20
5	Sewerage tunnel	Trickling water	Occasional drops of water	1.00	0.50

Table 1 : STUVA recommendations for watertightness (ITA 1991)

all aspects of spray applied waterproofing membranes can be found in the ITAtech report on these membranes (ITAtech 2013) so this subject will not be discussed in more detail here. The bonded nature of spray applied membranes also opens the door for the design of truly composite shell linings with an integral waterproofing layer (Thomas & Dimmock 2017 and Thomas 2019).

There are also examples of PSCL tunnels without any waterproofing membrane such as the Vereina and Furka tunnels in Switzerland or Heathrow Terminal 5, UK, in relatively impermeable ground. Much more rarely, there are tunnels where permanent concrete has been sprayed onto sheet membranes, although this is technically difficult to do and often not viable economically.

PSCL is often used in tunnels which have a drained design concept, commonly with an open invert, such as in Scandinavia. There, water ingress is permitted, and this is removed from the tunnel via longitudinal drains. The water is either actively directed from the tunnel vault to drains in the invert (e.g. using half-pipe drains, meshes of small half-pipes, strip drains or dripsheds) or passively by making the ground or the upper part of the lining more impermeable (e.g. by

systematic pre-grouting of the ground or by adding a spray applied membrane to the lining).

Depending on the waterproofing system, the intrinsic impermeability of the sprayed concrete may be relevant. Water permeability can be assessed by means of a penetration test (EN 12390-8) with penetration depths of less than 50 mm indicating good quality, impermeable concrete. Results from the extensive Brite Euram (1998) research project, an in-depth research project into the mix design and mechanical properties of sprayed concrete, found water permeability ranging from 0.5 to 4.5 x 10⁻¹² m/s and chloride diffusion coefficients ranging from 1.6 to 9.2 x 10⁻¹² m/s (Thomas 2019). A study in Norway (Holter, 2015) suggests that permeabilities in the range of 10⁻¹⁴ to 10⁻¹⁵ m/s (measured at 400 days age, cured in-situ in the tunnel lining) of the intact sprayed concrete material can be achieved in-situ when observing strict requirements on mix design, particularly the maximum allowed water-binder ratio, and the way the concrete is applied. Further details are given in reference case Gervings, see chapter 15, appendix 1. However, there are inevitably cracks within the lining, for example due to shrinkage and at the joints between each round. In-situ lining permeabilities

are documented in study by Celestino (Celestino, 2001), where back-calculated permeabilities are in the range of 10⁻⁸ - 10⁻¹⁰ m/s.

As discussed later in this section, this does not present a significant problem for the concrete itself in most cases, if the mix and lining concept has been designed appropriately for the groundwater conditions.

This leads to the question of the impact of water in the lining on reinforcement. For this reason, PSCL is often associated with fibre reinforcement because removing steel reinforcing bars removes a major durability concern. Steel fibres are much less vulnerable to corrosion because, unlike bar reinforcement, there is no risk of shadowing or spalling. Nevertheless, any steel fibres that bridge cracks are exposed and, while corrosion of the fibres will not cause corrosive spalling, it does reduce the load capacity (Nordstrom 2016).

Various researchers have examined cracked samples of steel and structural macrosynthetic fibre reinforced concrete under different exposure conditions and the conclusion appears to be that so long as the cracks are narrow (< 0.1 mm (Nordstrom 2017) or < 0.15 to 0.20 mm (AFTES 2013)), the loss of capacity may be small for steel fibres (see also chapter 7.3.4). In the narrower cracks, autogenous healing of the concrete may occur so the loss in capacity may not be significant. Macrosynthetic fibres do not generally corrode so the crack width is not a problem from the point of view of the integrity of the reinforcement.

Regarding the risk of permeation of water through the lining, a distinction should be drawn between flexural cracks, which do not run all the way through the lining, and shrinkage or direct tension cracks, which could provide water paths and therefore must be avoided. Countermeasures for the latter could include: changes to the design to reduce tensile forces; installing re-injectable grout tubes at high risk areas, such as the joints between bays when spraying a secondary lining or at tunnel junctions;

installing drainage channels; or installing a waterproof membrane.

6.7 DESIGN SPECIFICATIONS

The design specifications must set down the required concrete properties of the applied PSCL and must ask for them to be regularly tested. There are multiple steps in the supply and application of sprayed concrete, from the fresh mix, via concrete pump to the operators. The final properties should be tested to ensure that they conform with the design.

7.1 GENERAL

Durability is resistance to degradation. The durability of a structure depends on the environment which it is exposed to, the duration and severity of the exposure and its inherent resistance to any attack from that environment. In the following chapter, the impact of chemical, climatic and biological conditions on the ways that sprayed concrete in underground structures degrades are described. The influences of the spray application process, the loading of the lining and mix design are then reviewed and discussed in the context of sources of attack. Countermeasures to reduce the effects of degradation for sprayed concrete are discussed in parallel.

7.2 EXPOSURE CONDITIONS

7.2.1 Chemical conditions

Exposure to degrading chemical compounds occurs principally due to geochemical exposure and external chemical exposure.

Geochemical exposure comes from seeping groundwater containing minerals which can alter the sprayed concrete. Sulphates and chlorides are the most frequently occurring minerals in groundwater that cause degradation.

Sulphate attack causes chemical degradation of the cement hydrates, for instance by a delayed ettringite formation causing a crystallization pressure (mechanical forces) or by thaumasite formation yielding in the decomposition of the cement matrix. Hence the effect of the sulphate reaction is reduced mechanical strength.

Chlorides can occur in groundwater in subsea conditions or in rock masses of evaporite origin. Chlorides have little effect on the hardened concrete but may cause corrosion of steel fibre reinforcement in cracked concrete (Nordstrom 2016 & Hagelia 2018).

There are several countermeasures to limit the effect of groundwater exposure.

Reducing the permeability of the concrete and controlling cracking below a certain crack width are the main measures. The thickness of the concrete can be increased in areas where the concrete will be exposed. Adding compounds into the cement, such as microsilica, fly ash and slag, creates a denser, more homogenous and less permeable concrete. Hence, there will be less exposure to seeping water and less degradation due to the minerals dissolved in it.

Using sulphate-resistant cement, which has low amounts of Tricalcium Aluminate (C_3A) in its clinker, can reduce the effect of sulphate exposure. However, the favourable effect on the durability when using sulphate-resistant cement is only achieved at water-cement ratios below 0.5.

It is important to acknowledge that absolute resistance of concrete material to chloride and sulphate attacks cannot be achieved. However, significantly improved resistance to such degradation is possible by combining different measures.

The most common type of external degrading chemicals is de-icing agents which contain chlorides, mostly Sodium Chloride (NaCl) or Calcium Chloride ($CaCl_2$). Such exposure will create a combined effect of freezing and chloride exposure which results in a mechanical degradation of the surface, known as salt-freezing surface scaling. Such exposure can occur in sprayed concrete tunnels where water and salt splashes from the roadway during the winter season. This type of degradation has proven difficult to avoid for sprayed concrete. Hence, a protective measure, in the form of a covering structure or a durable surface sealant, is required.

7.2.2 Climatic conditions: air temperature and humidity

Several degrading mechanisms can result from changes in temperature and humidity. The most notable is freeze-thaw: when water freezes to become ice and, in doing so, expands.

Freeze-thaw occurs in climates where temperatures fall below $0^{\circ}C$, up to around 1km from tunnel portals.

Degradation due to freeze-thaw is significant and most commonly occurs due to poor workmanship in applying the sprayed concrete. Water contained in the micro pore structure of the concrete, due to capillary porosity, will have little effect during freezing, unless the concrete is almost completely saturated with water (more than 97-98 % degree of capillary saturation (DCS)). In practice, sprayed concrete linings which are exposed to air in the tunnel, will always almost exhibit lower degrees of saturation than this critical value (Holter, 2015). However, coarser pores and inhomogeneities are particularly prone to freezing damage. Such voids are typically caused by poor compaction during spraying, spraying 'shadows' due to a poor nozzle angle or orientation, irregular or rough rock surfaces or spraying onto rebars or lattice girders. Rebound which is covered during spraying creates large permeable pores. A high water-cement ratio (> 0.5) is likely to create a larger portion of permeable pores.

The main measure to avoid damage due to the formation of ice in the sprayed concrete structure is to apply a high-quality material with as few inhomogeneities as possible. Keeping the water-cement ratio low reduces the extent of permeable pores. Ensuring a good spray application technique reduces the possibility of large spraying voids and shadows.

Thermal fluctuations will result in thermally-induced contraction or expansion, which is governed by the thermal expansion coefficient of the concrete. Significant fluctuations of air humidity, leading to cyclic drying and moistening of the concrete, will result in shrinkage fluctuations and the resulting strains

In hotter and drier climates there are challenges due to the extensive drying out of concrete and the shorter drying times. Thin applied layers might exhibit lower bonding strength in these conditions, leading to debonding.

7.2.3 Biological conditions

Although it is a relatively rare occurrence, biological degradation of sprayed concrete can occur under certain temperature and humidity conditions in areas exposed to wet air, which are confined without ventilation over long periods. Biological degradation occurs when organisms grow on the concrete, producing chemicals which can then dissolve in water and – over time – start corroding the concrete.

Areas behind drainage shields or drainage strips with an air gap are typically prone to this. The contents of tunnels may also create a risk of biogenic corrosion, for instance in sewers. Such degradation occurs on the surface and in cracks in the concrete.

The best countermeasures are to avoid such confined air gaps if possible, to increase the thickness of the concrete and reduce crack widths, to reduce water seepage so that the tunnel is literally dry, if appropriate, and to introduce ventilation.

7.3 INFLUENCES ON DURABILITY

All the durability considerations of normal cast concrete apply to sprayed concrete as well. In this report, only the durability issues which relate particularly to sprayed concrete are addressed: the spray application, the loading and exposure of the concrete layer, special mix design considerations and means of reinforcement.

7.3.1 Durability issues influenced by the spray application process

For sprayed concrete, it is the spray application process that provides the compaction. Irregular or insufficient compaction will compromise several properties of the concrete, which in turn will reduce its durability.

Today PSCL is almost exclusively executed with the wet-mix method and spraying robots (see chapters 10 and 16 (Appendix 2). This requires a high-capacity concrete pump and the addition of pressurized air

and accelerator at the nozzle. This produces a high-velocity spray of wet concrete from the nozzle to the receiving substrate. The compaction of the concrete takes place at the impact of the concrete on the substrate. Once it has hit the surface, the concrete remains somewhat wet for one or two seconds before the initial set occurs, producing a solid concrete material which sticks to the rock surface or concrete.

The main consequence of poor compaction is the increased occurrence of open macropores, often in the form of open voids, larger than 10 mm. Such pores provide channels for leaking water and hence decrease the concrete's resistance to leaching (where water dissolves compounds inside the pore walls within the concrete), chemical degradation and freeze-thaw attack.

Proper compaction can be achieved by ensuring correct spray application parameters such as nozzle distance, nozzle angle to the rock surface, and by advancing from the invert upwards, to avoid spraying over rebound. Physical conditions during spraying also impact on compaction. The right concrete temperature, avoiding spraying at very low temperatures (freezing) and thoroughly pre-wetting of the substrate immediately before spraying all contribute to good compaction. Note that pre-wetting is essential when spraying onto already hardened concrete, but not possible when spraying onto soft ground (see also chapter 16 (Appendix 2)).

Compaction of sprayed concrete can be assessed through visual observations, recording irregularities and voids exposed in the surface, and recording macro pores and voids in drilled cores. Such testing should be carried out very early in a project so that the spraying procedure can be corrected if necessary.

7.3.2 The insitu loading and exposure of the sprayed concrete

The sprayed concrete is directly bonded to the ground on one side and exposed to

the air or a lining material on the other. It will be subject to insitu loading and physical, mechanical and chemical factors which may influence its durability:

- Exposure to running or seeping water which, in the long term, causes leaching, and can introduce aggressive ions such as sulphates and chlorides.
- Exposure to thermal gradients and fluctuations which cause fluctuating thermally-induced strains in the concrete.
- Exposure to fluctuations of relative air humidity in the air in the tunnel, which causes fluctuations in the moisture content of the concrete and hence fluctuating strains and shrinkage.

These factors can be influenced by the design of the sprayed concrete lining and the design of the whole tunnel structure. In principle, an undrained, completely bonded lining structure with no draining of water through the sprayed concrete is much less prone to degradation than a design which allows water to drain through the sprayed concrete.

7.3.3 Mix design & steps to improve durability

The mix design can be optimized to improve the concrete's durability, tailored to the particular exposure risks of each project. This generally involves making the concrete as impermeable as possible. Measures to improve the density and permeability of normal cast concrete have an even larger effect on sprayed concrete:

- Maintain the water-binder ratio as low as possible and never above 0.5. This increases the mechanical strength of the concrete and also ensures a dense material with extremely low hydraulic conductivity. Adjust the components of a mix to combat chemical attacks and to minimise the risk of leaching which causes sintering, or clogging, of drainage (see 7.2.1).
- Use of aggregates which fall within the recommended range of the aggregate grain size gradation curve (see also chapter 9).

- Using admixtures to increase the concrete density but note the risk of shrinkage due to thermal effects (see 6.4.)

Adding microsilica, a mineral admixture, to a mix improves the strength performance of the concrete, and also makes it denser and less permeable. This is due to the effect of the microsilica on the concrete in its fresh, wet condition during pumping and spraying. However, note that microsilica does result in a more brittle concrete which is more prone to thermal cracking. The challenge is to find the balance between density and thermal cracking.

The effect of these measures on durability can be measured indirectly in the laboratory by density and water penetrability tests on samples of hardened concrete as described in EN 12390 – see also 14.7.

7.3.4 Durability of reinforcement

The design philosophy behind permanent sprayed concrete aims to avoid steel reinforcing bars wherever possible. This minimises the risk of corrosion since steel fibres do not corrode when embedded in the concrete and macrosynthetic fibres do not corrode in most common exposure conditions (Bernard, E.S. & Thomas, A.H. (2020))

Steel reinforcing bars may be needed in some cases, for example, as extra reinforcement at junctions. In these cases, the usual requirements for reinforced concrete regarding cover and crack width apply.

Reinforcement for sprayed concrete in soft ground, which is often lattice girders and mesh, must be properly embedded in the concrete. If concrete is sprayed improperly

through lapping mesh, it can create large voids, spray shadows, low compaction and related low strength. Mesh should have a minimum grid of 150 by 150mm to minimise these potential negative impacts.

A dense concrete limit the ability of harmful substances from penetrating the concrete and reaching the steel – primarily water, chlorides, oxygen and carbon dioxide. If steel bars are used within a lining which is mainly fibre reinforced, they will benefit from the general reduction in cracking due to the fibres, as described below (see also 10.5).

Fibres can be used to replace mesh, avoiding the challenges mentioned above and providing ductility and residual flexural tensile strength to sprayed concrete. Steel fibres bridging open cracks can corrode. In a less aggressive environment, this applies to cracks over 0.2 mm. In aggressive environments, this applies to cracks over 0.1 mm (ITatech 2016 & Nordstrom 2016). For this reason, it has been suggested that the minimum thickness for PSCL should be at least 80 mm (current practice with Norwegian Public Road Administration and Norwegian National Rail Administration).

Based on the experience of Norwegian tunnels, Hagelia (2018) has suggested various minimum thicknesses of fibre-reinforced sprayed concrete (see Table 2), depending on the Eurocode exposure classes. Note that this is based on data for only a quarter of the typical design life and that most rock conditions encountered in Norway are good which means that most linings are subject to light or local loads.

Crack widths can be limited in the design by limiting the tensile stresses in the lining and by carefully choosing the mix design (see 6.4). Narrow cracks may close over time

due to autogenous healing and it is worth bearing in mind that cracks in fibre-reinforced concrete tend to be more tortuous than in bar-reinforced concrete (so-called 'crack branching'), which reduces the risk further. In general, fibre reinforcement reduces the permeability of cracked concrete (ACI 544.5R-10 2010).

7.4 MAINTENANCE

In addition to the measures discussed above, the longevity of a tunnel lining, like any concrete structure, can be improved by regular monitoring and, where necessary maintenance, ideally preventative maintenance. In practice, many clients prefer to limit maintenance due to operational considerations which places more emphasis on the preventative steps listed above. This may dictate refinements to a basic PSCL design. For example, in the specific case of a road tunnel where a smooth, reflective surface is needed at the road level, a cast sidewall may be preferred, while a rougher sprayed concrete surface which is very hard to clean is acceptable in the crown. Generally speaking, a significant benefit of PSCL tunnels is that they can be designed so that little or no maintenance of the lining is required during their operational lives.

ENVIRONMENT & EXPOSURE CLASS ACCORDING TO EUROCODES			
Freshwater	Mildly acidic	Alum shale rock	Subsea tunnels
XC2 – XC4	XC 2	XC2 – XC4	XC2 – XC4
XD1 – XD3	XD0	XD0 – XD3	XD0 – XD3
X0	XA1	XSA	XS3, XA2-XA3
80 mm	80 - 100 mm	100 – 150 mm	100 mm

Table 2 : Recommended minimum thickness of fibre reinforced sprayed concrete for permanent rock support (after Hagelia 2018)

Sustainability is a very broad subject which encompasses our impact on the environment and how this can be reduced to a manageable level. There is an increasing trend towards incorporating the assessment of this impact into engineering projects as part of a Life-Cycle Assessment (e.g. in the framework of ISO 14044:2006 - see Kodymova et al 2017).

When considering the use of PSCL instead of a more traditional solution, there are two important questions :

- Does the use of PSCL reduce the overall carbon footprint and other environmental impacts of the project?
- Does the use of PSCL make underground space more viable as a sustainable solution to infrastructure demands?

8.1 CARBON FOOTPRINT

Embodied carbon in a structure, or its carbon footprint, arises from the materials in it and the construction processes. In the context of PSCL tunnels, there are three primary sources of embodied carbon: excavation (and mucking out), concrete and steel. The carbon embodied in the materials arises from their production, transport and application. While there are many other components to a PSCL tunnel, these are the most significant and the following section will focus on them.

A comparison between PSCL and a traditional double shell lining (DSL) has been made for two cases: a hard rock tunnel and a weak rock tunnel.

Both tunnels are the same size (approximately 100m²) with a drained design concept. Table 3 lists the key geometrical parameters. The PSCL options have a spray applied waterproofing membrane (SAWM) which requires a regulating layer (a total thickness of 40mm is assumed) while the DSL options have a traditional PVC sheet membrane).

Figure 3 and Figure 4 are based on the embodied carbon in the materials only, using typical data. No specific allowances have been made for items which are common to both types of tunnel or not related to the tunnel lining itself (such as the rock bolts for the hard rock tunnel or internal works).

ITEM	Hard rock PSCL	Hard rock DSL	Weak rock PSCL	Weak rock DSL
Primary lining concrete thickness	80	80	200	200
Primary fibre / bar (kg / m ²)	40	40	8	37
	Steel fibre	Steel fibre	Macrosynthetic fibre	Steel mesh
Membrane (mm)	40	0	40	0
	SAWM	PVC sheet	SAWM	PVC sheet
Secondary lining concrete thickness (mm)	80	300	150	300
Secondary steel fibre / bar (kg / m ²)	40	97	40	97
	Steel fibre	Steel bar ³	Steel fibre ⁴	Steel bar

Table 3 : Key parameters for the comparison between PSCL and DSL carbon footprints

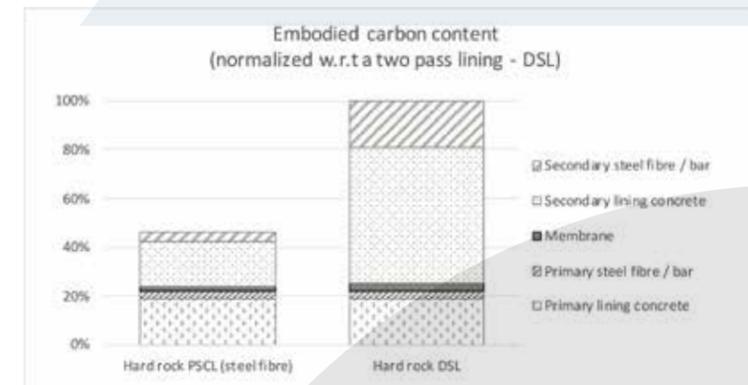


Figure 3 : Embodied carbon for hard rock tunnel linings (normalized w.r.t a two pass lining - DSL)

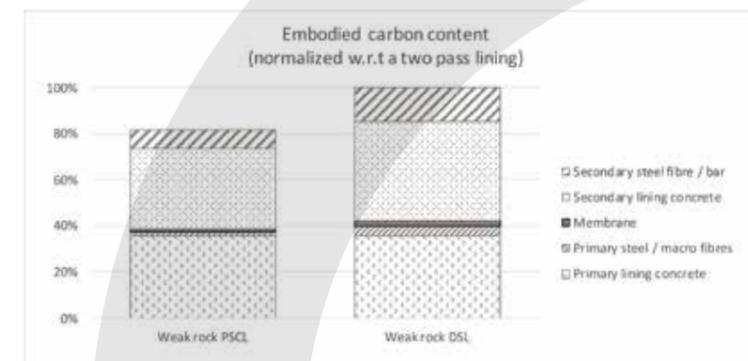


Figure 4 : Embodied carbon for weak rock tunnel linings (normalized w.r.t a two pass lining - DSL)

³The inner lining could be designed as an unreinforced concrete and in some countries, this is standard practice.
⁴Macrosynthetic fibres could also be used for the secondary lining but the example here follows the design of a real case study in which they were only used for the primary lining.

In both cases, the PSCL option has a lower embodied carbon content than the traditional double shell lining. Even though sprayed concrete has a higher embodied carbon content than cast concrete per cubic metre due to its higher cement content, the need for less material in the sprayed concrete tunnel results in a lower carbon footprint. Similarly, a kilogramme of steel fibres has a higher embodied carbon content than a kilogramme of plain reinforcing steel bars. However, the mass of fibres is much lower in a PSCL secondary lining than the mass of bar reinforcement in a cast-in-place secondary lining.

This simple but conservative comparison suggests that the PSCL option could have a 20% to 50% lower carbon footprint than the traditional option. Obviously, these calculations will vary depending on the specific characteristics of each project and the sources of the materials.

In terms of further improving the sustainability of a tunnelling project, one must remember to consider the project as a whole. Other options, which could be considered to improve the sustainability of the sprayed concrete lined tunnel, include:

- Minimizing transport distances.
- Using recycled aggregates.
- Selecting steel products with a higher proportion of recycled steel.
- Refining the mix design to use more cement replacements or geopolymers technology (if appropriate).
- Using macrosynthetic fibres instead of steel fibres (if appropriate).

8.2 PRIMARY SUPPORT CONSIDERED PERMANENT - MATERIALS CONSUMPTION

Using the primary support as part of the permanent lining system reduces the material requirements on a project and therefore offers a more sustainable solution to the alternative.

One example of this is the A3 Road project in Hindhead, UK where a significant reduction in the total concrete required on the project

was achieved through the use of permanent sprayed concrete. Details of the lining design adopted at Hindhead are shown in Figure 5 below.

Two hard rock examples are shown in Figure 6. For the Gevingås rail tunnel, the PSCL support follows the excavation contour over a 1.85km stretch of the 4.1 km-long tunnel, thus minimizing the overall sprayed concrete volume. In the Holmestrand rail tunnel, a 90m-long portion of the tunnel through difficult ground was constructed with a PSCL-based lining. Both projects were waterproofed with a spray-applied double bonded membrane.

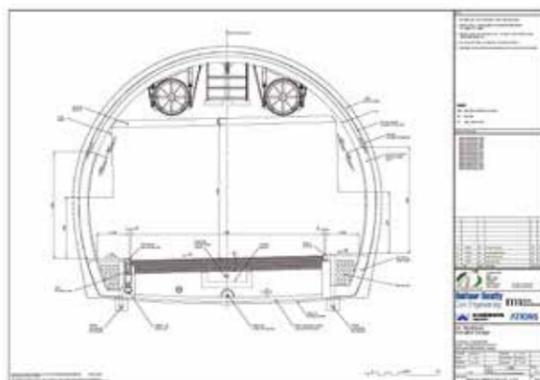


Figure 5 : Cross-section of A3 Hindhead road tunnel (opened 2011)



Figure 6 : Recently constructed PSCL tunnels in Norway. Right: The Holmestrand rail tunnel, constructed 2012-2015, portion in mixed face with soil and hard rock, with waterproof PSCL in the foreground and the interface to the traditional concrete segment waterproofing shield system. Left: Gevingås rail tunnel, constructed 2009-2011; meta-greywacke (meta clay/sandstone), groundwater table approximately 80 m above the tunnel crown, drained invert (Photos: Karl Gunnar Holter)

Sprayed concrete is a combination of materials, equipment technology and applicator skills. The mix design must take this into account. The way that the concrete performs through the steps between batching plant, transport, pumping and its application to the substrate all influence the concrete's final properties.

9.1 ASPECTS OF PSCL AFFECTED BY THE MIX DESIGN

The mix design for PSCL should follow the general standards for concrete and sprayed concrete. For example, the relevant European standards are:

- EN 206 (specifications, performance, and production with respect to constituents and concrete)
- EN 14487 (Definition, specifications, conformity, and execution of sprayed concrete)
- EN 934-5 (Definition and requirements for admixtures for sprayed concrete)

Important properties of the fresh sprayed concrete mix which are related to the application method and the intended use are covered below.

9.1.1 Workability

Workability allows for the high degree of flexibility required in underground construction, so that smooth pumping and spraying is possible over a prolonged period if necessary. Even when spraying is delayed, the concrete should mix homogeneously with the accelerator and allow good spraying, for example around reinforcement (see 10.5).

A suitably workable mix would be plastic, not too sticky, non-bleeding with sufficient open time. Such a mix requires even and continuous grading, a suitable fines content (paste volume), a reasonably reactive cement, non-polluted water and appropriate admixtures and other concrete additions. The fresh concrete properties should be verified by using one of the two standard measurement methods, namely the slump cone retention or the DIN flow table; both measurements supplemented by a visual

bleeding assessment. It should be added, that the DIN flow table allows for a better assessment of fresh concrete parameters through its dropping, better simulating the dynamic pumping impact.

9.1.2 Pumpability

Good pumpability of the mixture is a must for dense-flow shotcrete application, not just to enable a continuous and uninterrupted transfer of material to the nozzle, but also to reduce or even eliminate any pulsing of the spray jet (pulsation) so that there can be homogeneous mixing of the accelerator. Well-balanced grading and paste volume, the use of superplasticizers and possibly air-entraining admixtures play key roles in achieving good pumpability.

9.1.3 Placing

Getting the (early) performance of sprayed concrete right is vital for construction speed and safety. The quality of the concrete should be as uniform as possible over a long period which can only be achieved if all materials and processes are as controlled as possible (see chapters 12 and 14). Achieving a high-quality sprayed concrete depends on the entire mix design (materials, workability, pumpability, plasticity) and an even, smooth process (equipment status, staff competence).

9.1.4 Safety

Besides the equipment and application methods (which are covered in chapters 11 and 16 (Appendix)), health and safety must also be considered during mix design, taking into account the components of the mix and any hazards that they may pose during handling, mixing and application. For example, spraying creates dust and rebound with some of the chemicals appearing in the form of aerosols. The mix design can be optimised to minimise both the immediate safety risks (falls of shotcrete) and occupational health risks (dust emissions) from these hazards.

The mix should be designed to minimise

the dust and to keep it within safe limits as defined by the relevant local regulations. Similarly, the chemicals used should comply with the relevant local safety regulations - during handling, mixing and application. BS 6164 (2019) is an example of guidance on good health and safety practice for these aspects.

9.2 DURABILITY

A PSCL needs to be durable, otherwise it isn't permanent. Durability is a collective term covering several shotcrete properties. These are explained in more detail in chapter 7, with the impact on mix design summarised below:

- Watertightness / leaching: if the shotcrete is too water permeable or the water pressure from the water head too high, or both, leaching of the shotcrete might occur, leading to a degradation of the strength of the cement matrix. Measures regarding the mix design should focus on a densely sprayed concrete lining.
- Chemical resistance, especially to sulphate attack: apart from the correct choice of materials and potential waterproofing measures, the density of the sprayed concrete (even grading, paste volume, microsilica) is crucial to avoid or suppress chemical attack on the sprayed concrete.

Freeze-thaw resistance: a dense sprayed concrete, with the addition of air-entraining admixtures, is required. Since the spraying process will reduce the air content of the concrete, pre-construction tests are advisable.

9.3 MIX DESIGN GUIDANCE

Mix designs for temporary sprayed concrete may also be appropriate for PSCL. Refer to locally-accepted mix design guidance but pay more attention to the application and ensure that quality control systems are appropriate.

As explained in chapter 7, achieving high density of the concrete lining is the key to durability and is vital for the use of PSCL. Limiting thermal cracking is also vital. This is

explained in 6.4 and summarised below, for unloaded or lightly-loaded linings:

- Ensure that the mix can be produced and applied safely, for example without producing harmful levels of dust or chemicals in aerosol form.
- Use a mix design with a balanced cement and water content (cement content not too high, water-cement ratio below 0.5).
- Include admixtures to lower the stiffness, such as polymers and air-entraining admixtures.
- The recommended range of fresh concrete temperatures delivered from batching plants is between about 15°C (experience based) and a maximal temperature of 22°C (Austrian Guideline for Inner Shell Concrete (2006)). Higher fresh concrete temperatures pose challenges which need to be dealt with separately.
- Limit the concrete heat development after accelerator addition by spraying at cooler (not cold) temperatures and avoiding unnecessarily high accelerator dosages. Dose the accelerator just enough to get the material to properly stick to the substrate without sagging – to reach upper J1/lower J2 curves at about 6-10 minutes, according to EN 14487-1.
- Add structural fibres to better distribute the occurring cracks.
- Create a good bond to the substrate by cleaning and prewetting (for concrete substrates). Bond-improving admixtures may help.
- Ensure proper curing and controlled ventilation. Consider using water mist, water, and internal curing admixtures if required. Ensure there is no direct air flow onto freshly applied layers.

Even the best mix design cannot overcome significant shortcomings in how the PSCL is applied. It is vital to use the right equipment and ensure that the operators are properly skilled and qualified. Detailed advice is given in the following chapter.

The difference between PSCL and temporary sprayed concrete is that PSCL has a longer design life. This is reflected in differences in mix design and quality control regimes. PSCL may also require a better final surface finish.

Detailed information and guidance on the placing of sprayed concrete can be found in chapter 16 (Appendix) as well as in several other documents, such as Austrian Guideline Sprayed Concrete (2013), the Norwegian Concrete Association Publication no.7 - Sprayed Concrete for Rock Support (2011) and EFNARC documents such as Nozzleman Assessor Training Course Notes and Checklist for Specifiers and Contractors (2002).

The following sections highlight the most important criteria for success when using PSCL.

10.1 BUILDABILITY

All construction quality is improved by a design which is simple to build. In both hard rock and soft ground, the inherent variability demands a pragmatic approach to specifying strengths, thicknesses, etc. Designers of PSCL tunnels should avoid shapes, details and arrangements of joints that are complicated as it will be hard to ensure high quality during construction.

Avoid steel bar reinforcement in PSCL wherever possible. It is worth noting that often the optimum method for constructing the lining in the invert may be casting bar-reinforced concrete. Combining sections of a lining that are cast and others that are sprayed may offer the optimum solution. In soft ground tunnels designers tend to adopt more rounded shapes for to permit the use of fibre reinforcement alone, reducing the need for additional bar reinforcement.

10.2 QUALITY CONTROL

As discussed above, a more comprehensive regime of quality assurance and control is required for PSCL, commensurate with its status as part of the permanent works.

This applies to pre-construction trials as well as the construction phase. Following the EFNARC checklist (EFNARC 2002) is a useful way of ensuring that all aspects are covered. For more information see also chapter 14 below and chapter 18 (Appendix).

10.3 SHAPE & THICKNESS CONTROL

In soft ground tunnels, shape control is important to minimise bending moments in the tunnel lining. In all cases, the design of the permanent lining is based on a minimum thickness of a certain grade of concrete.

There is a welcome trend to replace traditional physical methods of checking shape and thickness, such as lattice girders, steel tell-tale pins and drilling holes, with advanced surveying methods using laser theodolites, laser scanning or stereographic photography.

These methods mitigate the risk of potential problems caused by the mesh or lattice girders (see 7.3.4). The new survey systems have been used successfully on large and small tunnels. Pioneering projects which have used these techniques include Heathrow Terminal 5, A3 Hindhead and Crossrail, all in the UK.

10.4 BOND

A permanent sprayed concrete lining may be built up in several passes, with layers possibly sprayed months apart. The risk of shrinkage stresses that could affect the bonding between the passes depends on several factors. These include the mix design, surface preparation, the atmosphere in the tunnel and the thickness of the layer.

For the whole lining to function as a single structural body, it is essential that there is a good bond between the various layers. This can be achieved by careful preparation of the substrate, noting the following points:

- Careful mix design checked with trial spraying.
- Jet washing to remove dust and

deleterious materials. Use enough pressure and volume of water to remove loose or weak material; spraying air and water out of the concrete spraying robot nozzle may not be sufficient in all cases.

- The substrate must be pre-wetted to ensure no water loss from the concrete at the contact zone between new and old sprayed concrete layers. The older, dry layer can extract water from the freshly applied layer, leading to insufficient curing and therefore lower bond strengths.
- Spraying should follow normal, good practice and the accelerator dosage should be kept as low as possible. Typically, this is less than 8%.

10.5 SPRAYING AROUND REINFORCING BARS

PSCL is often fibre reinforced, but there may be occasions where bars are needed to provide significant bending capacity, for example, at junctions in soft ground tunnels. Glass Fibre Reinforced Polymer (GFRP) bars can be used as a non-corroding option.

If steel bars are used, it is important to ensure that they are fully encased in concrete to avoid corrosion. In practice, it is best to limit the diameter of steel bars to 16 mm or smaller (Fischer & Hofmann 2015) or 14 mm (Austrian Guideline Sprayed Concrete 2013).

Bars up to 40 mm have been sprayed in successfully but this is very difficult to do, especially where the bars lap or cross. Multiple layers of smaller bars should be considered as an alternative to large-diameter bars.

The spacing of bars laterally seems to be less critical but the minimum practical spacing is about 100 mm. The bars should be placed as close to the substrate as possible.

Spraying overhead is more difficult than spraying at the side of the tunnel (Fischer & Hofmann 2015).

10.6 SURFACE FINISH

The surface finish will depend on the purpose of the tunnel. For instance, if steel fibres are used in a tunnel for public use, a smoothing layer may be required for safety to cover any protruding fibres. The smoothing layer is typically 25 to 50mm thick and it can be sprayed either wet or dry. It is important to ensure a good bond to the main body of the lining – see also 16.2.

10.7 TEMPORARY DRAINAGE

This section covers measures that may be required temporarily during the application of the sprayed concrete. Watertightness during operation is covered in 6.6.

Water ingress during spraying must be controlled to ensure that the concrete bonds properly to the substrate. This is usually only an issue when spraying the primary layer. It is very important to capture all water inflow using adequate drainage.

Isolated water inflow can be controlled by using half pipe drains, while larger surfaces must be drained with drainage layers or eliminated by pre-grouting or post-grouting. Temporary drainage measures should be designed with the overall waterproofing concept in mind so that there is no conflict between them.

10.8 CURING

Proper curing improves the sprayed concrete strength, increases the bond between layers and helps to minimise shrinkage cracks. The Austrian Guideline Sprayed Concrete (2013) requires curing for sprayed concrete only when it has special properties, whereas the Norwegian Concrete Association Publication no. 7 – 2011, 2021 - Sprayed concrete for rock support (NB 7), provides more detailed advice. The Norwegian guidance says that freshly placed sprayed concrete must be protected from excessive drying for at least four days and special attention is to be paid to ventilation, especially during winter, due to the dryness of cold air blown into the tunnel. In addition to water spraying as a curing measure, internal curing agents are mentioned, which are to be added at the batching plant.

The safety risks, including occupational health risks, should be reviewed for each specific tunnel project, in line with the relevant local safety regulations. This starts with a review of the health and safety risks during the design phase. The review of risks and risk management continues during the construction phase and ultimately during the long service life and operation of the tunnel. Where local regulations do not exist, good international practice should be adopted (e.g. BS 6164 (2019)).

Since sprayed concrete is a durable and inert substance, the choice of a PSCL generally does not introduce any design safety concerns for the operational phase. The only caveat is that where steel fibres are used, the protruding fibres on the surface of the concrete should be covered, if there is a risk of people coming into contact with them during operation.

More broadly, the risks for both occupational health and safety tend to be associated with the construction of the lining (Thomas 2019) in terms of handling the materials, operation of the equipment and the application of the sprayed concrete. In general, the risks associated with PSCL projects are the same as for any application of sprayed concrete.

Some general guidance on risk management is provided below, together with more detailed information on two areas of particular concern: how to avoid falls of sprayed concrete and risk considerations related to dust.

11.1 RISK ASSESSMENT & MANAGEMENT

Each project team should conduct its own risk assessment for their project and its particular conditions. For all activities, control measures should be identified to eliminate or minimise, so far as is reasonably practicable, risks associated with the SCL tunnelling work. Occupational health risks during construction, which are sometimes neglected, should receive particular attention.

If elimination of a hazard is not possible, measures should be taken to minimise exposure and mitigate the risks, for example, through the use of mechanization, ventilation, shift length reduction or rotation, or substitution of materials. Monitoring of various hazards may also be required.

There should be procedures in place for the handover of safety-critical information between the different phases of a project, and at the changeover between shifts during construction. Information on general tunnelling construction risks can be found in standard texts (such as the publications from ITA Working Group 5: Health and Safety in Underground Works and BS 6164 (2019)).

11.2 RISKS FROM FALLS OF SPRAYED CONCRETE

Tragically falls of sprayed concrete have recently resulted in fatalities to workers on major projects in the UK and US. Falls of sprayed concrete in tunnels can occur for various reasons. These include poor substrate preparation; inadequate concrete mix, including additive dosage; inexperienced operator and poor spraying techniques; too rapid build-up of thick layers and inappropriate equipment type or settings. Although the wider use of robotic rather than hand spraying reduces the risk of injuries or fatalities from falls, deaths have still occurred when robotic sprayers were in use.

One obvious solution is to restrict worker access temporarily to areas of the sprayed concrete tunnel lining at risk. These areas are commonly called 'exclusion zones'. Typically, exclusion zones are needed close to the tunnel face during tunnel excavation and installation of the primary lining, especially the top heading and bench (above the tunnel axis). Exclusion zones are also needed anywhere where the upper arch of the secondary sprayed concrete lining is under construction. Often 'restriction zones' are also designated adjacent to exclusion zones to restrict access to non-essential personnel.

Only those with designated roles and responsibilities for construction and quality inspection can enter these zones.

Exclusion zones must be carefully managed by a designated, competent person. Typically, exclusion zones include a physical barrier and warning signs restricting all personnel access. A challenge is controlling when to remove the exclusion zone and allow access. The Crossrail project in the UK issued a best practice document which recommends implementing both a minimum time after completion of spraying and a minimum strength before the exclusion zone is removed (Crossrail 2016). The test is typically based on penetrometer testing of the early-age compressive strength of sprayed concrete panels located outside the exclusion zone and produced immediately after spraying the tunnel lining. The minimum strength before re-entry on Crossrail was 0.5 MPa (King et al 2016).

Falls of sprayed concrete can also be associated with falls of soils or rock during tunnel excavation. Exclusion zones should be considered during the excavation process as well as the spraying process. With soft ground tunnelling, the excavation and spraying operations may frequently alternate, depending on the size of the heading and stand-up time of the soils.

It is good practice to record, save and analyse all data associated with falls of sprayed concrete, including all data from the spraying equipment itself, to assist in identifying the root causes of the falls. Such events should be recorded as a safety 'near miss'.

One innovation which may help reduce the risk of concrete falls is the use of thermal imaging cameras to monitor the rate and extent of strength gain of the sprayed concrete from a remote and safe area. As the camera and software technology improves in the future, and confidence in this method increases, it may be possible to use it instead of sprayed concrete test panels. (SMUTI, Strength monitoring Using Thermal Imaging, winner of the Technical Product Innovation, ITA Awards 2017).

11.3 DUST

Strict limits for dust exposure, particularly respirable dust and respirable α -quartz (a human carcinogen) should be observed. With a well laid-out application process with respect to ventilation and exposure of the operator, it is possible to achieve low levels of dust exposure well within Occupational exposure limits (OELs).

Any sprayed concrete works involve the risk of respirable dust. This should be mitigated primarily with good ventilation minimising the need for personal protective equipment (PPE) (see chapter 16 (Appendix)). The layout and organisation of the works plays an important part in limiting exposure to dust during the spray. The spray operator should stand on the floor of the tunnel, several metres from the spraying, positioned so that the ventilation system is moving dust away from the operator at a sufficient speed to contain the dust.

Thorough measurements of respirable dust for underground construction workers during sprayed concrete works in tunnelling (Bakke et al 2001) show that both total dust and respirable dust are present in significant amounts for sprayed concrete operators. Bakke's extensive study showed that positioning shotcrete operators carefully, as described above, gave respirable dust and respirable α -quartz (crystalline silica) values that were consistently below the OELs.

Note that OELs for respirable α -quartz are currently under scrutiny and vary around the world. These may be reduced in the near future.

The competence of the operator is at least as important as the equipment used and the composition of the material in determining the end quality, safety and cost of PSCL. The operator must be capable of spraying properly to produce a dense concrete that satisfies the design, meets quality requirements and ultimately is safe during the construction and operation periods. Improper application increases rebound, fallouts and over-spraying, adding to the total material usage and the total cost of the project. Inadequately skilled operators also increase the wear and tear on the equipment and can even severely damage it. This increases downtime and further adds to the cost.

All operators working with sprayed concrete should have gone through a structured and objective training course leading to a certificated operator status. This section suggests how this training could be set up, provides examples of already established training and certification schemes, and discusses how to set guidelines for staff and competence training.

Since the trend, all over the world, is away from hand spraying towards mechanized application with spraying machines, these guidelines focus on mechanized application. For hand spraying, ACI CP-60 provides guidelines and examination procedures for hand spraying of structures in North America. ASQUAPRO, the French association for the quality of sprayed concrete provides examination and certification procedures for manual spraying, as well as mechanized spraying.

In the future, it is likely that more automated spraying machines will be used. This will improve the working environment and reduce monotonous and strenuous manual work. However, even with this improvement, operators will still need proper training and competence to monitor the process and execute corrective actions. Parallels can be drawn to the aerospace industry, where planes can fly themselves, but competent and skilled pilots are still required.

12.1 TRAINING

The aim of training is to equip both novice and experienced operators with the necessary knowledge and skills to perform safe, high-quality, efficient and cost-effective sprayed concrete.

The training should be structured and contain theory (including an examination), a session on sprayed concrete test methods and, if possible, simulator training and assessments. It should also, after initial training, include structured onsite training or on-the-job supervised training or apprenticeships for some months.

12.1.1 Theory

Lessons on theory are important because they help operators to understand all the inter-related aspects of PSCL. Subjects should include concrete technology; spraying equipment; designers' expectations; application; preparing the tunnel area and substrate; surface finishing and curing; thickness control; the cost structure of sprayed concrete and the cost impacts of operators' actions; standards and testing; safety, health and environment; and rules and regulations relevant for the local or national area. The operators' knowledge should be tested with a theory examination, which has a predetermined pass mark.

12.1.2 Concrete test methods

Learning about concrete test methods helps operators to better understand the behaviour of the sprayed concrete. Different tests should be performed looking at the properties of the sprayed concrete material. These tests include fresh concrete tests like the flow-test (EN 12350-5); slump test; measuring air and fibre content; mixing concrete with different accelerator dosages to understand the setting and strength gain; and strength tests on the placed material with a penetration needle and Hilti gun or a penetrometer.

12.1.3 Simulator training and assessments

This new technology allows for improved and cost-effective training using concrete

spraying simulators in Virtual Reality (VR) – see Figure 7. VR simulators put operators in close-to-real conditions, immersing them in a controlled and safe environment. There is no risk of damage to equipment and an indefinite amount of sprayed concrete material can be used for training without the normal cost associated with this. Using simulators also allows for objective assessments of an operator's skills, competence and their ability to conduct safe, efficient and cost-effective concrete spraying, judged against the set requirements.



Figure 7 : Virtual reality training and assessment conducted at E4 Stockholm Bypass project in Stockholm, Sweden as a part of the Swedish Transport Administration's certification scheme. © 2019 Edvirt AB. All rights reserved.

VR simulator training and assessments should normally be performed during a period of 20 to 40 hours, with operators going through different scenarios testing their skills and competence. Operators should be tested on and understand procedures such as start up and shut down procedures; surface preparation; safety procedures; manoeuvring the robot joints and booms via a remote control; setting the angle and distance from nozzle to surface; concrete pump output; accelerator dosage; concrete setting; thickness control; over-spraying; rebound requirements; avoiding fallouts; spraying over-breaks; spraying slopes; time-limited spraying; corner spraying and face spraying.

Both novice and experienced operators should be tested with a simulator, since experience does not always equate to good performance. Putting all operators through the same training will ensure an appropriate

minimum level of skill and competence for all operators.

12.1.4 Concrete spraying as training

The alternative to simulator training is designated spraying training, where concrete is sprayed in real conditions, for instance using a mock-up tunnel to spray 50 to 100 cubic metres. This approach might be more realistic, but is also significantly more expensive, cumbersome to organize and increases risks to both operators and equipment.

Another alternative is on-the-job training where operators are trained during real production, say for six to 12 months. In this approach, it is vital not to jeopardize safety and quality at site, as the trainee operators will be spraying the real support structure. It is important to have designated trainers who can quality assure all aspects of the spraying and prevent new operators from picking up bad habits.

12.1.5 Period of supervised onsite training / apprenticeships

A period of supervised on-site training or apprenticeship of, say two to four months, should be a part of the training procedure to ensure that good practice and behaviours continue after the basic training.

12.1.6 Recommendations

It is best to train operators by using simulator training or spray training on mock-ups or test bays outside the final structure. Using external experts on sprayed concrete application for training will add objectivity and quality.

12.2 CERTIFICATION SCHEMES

Currently there are several different certifications schemes operating in the world which have been adopted by many different projects. For more information see chapter 17 (Appendix 3).

12.3 SETTING REQUIREMENTS FOR CERTIFICATION

Often the client or main contractor assumes that operators are skilled enough, which is not always the case. Since all tunnel projects benefit from properly-placed sprayed concrete, requirements for the skill of spray operators should be specified at an early stage. A certification scheme is therefore beneficial, as it combines both training and assessment.

The certification scheme should be objective and non-biased. It should not rely on subjective assessments which may vary from project to project. Tools such as simulators can be used, and outsourcing can be considered. As local training standards may vary, referring to globally used and accepted standards helps avoid grey areas in comparing the skill sets of operators.

A good specification should be comprehensive, yet concise and unambiguous. Typically, a specification for PSCL defines the inputs required (i.e. materials and competences of key staff), methods (how to build the structure and the management processes) and the quality of the final product (e.g. strengths, geometric tolerances, durability, watertightness). More detail is not included here, since there are several published guides that can be used as a basis for a project's specification (see Table 4).

Chapters 12, 16 and 17 provide more information on application and competence while chapters 14 and 18 cover testing.

SPECIFICATIONS	COUNTRY
EN 14487 (2006) & EN 14488 (2005, 2006) along with Eurocodes	EU
ACI 506.2 (2018), ACI 506.5R-09 (2019) & ACI 506R-16 (2016) & ASTM C1436 – 13	USA
JSCE Guideline for Concrete Nr.8	Japan
BTS (2010) Specification for tunnelling 3rd edition	UK
EFNARC (1996 & 1999)	Europe
OBV (2013) Sprayed Concrete Guideline	Austria
NB 7 (2011, 2021) Sprayed Concrete for Rock Support	Norway

Table 4 : Common sprayed concrete specifications

A high-quality, durable PSCL requires the right material to be applied by competent operators, using the right equipment. The testing regime for PSCL should be designed to verify this.

Testing is required during pre-construction, to develop the best mix design for a PSCL project and during construction to demonstrate that the required performance is being achieved. During both the pre-construction and construction phases, tests should be carried out on the constituent materials, on the fresh mix and on the sprayed concrete.

The sections, below, outline what testing should achieve during the pre-construction and construction phases. Additional notes relating to aspects which are specific to PSCL follow: accelerators, long-term strength and fibre-reinforced concrete. Finally, there is guidance on the testing methods which can be used, and a section devoted to durability testing. This chapter does not cover specialist subjects such as performance in fires.

14.1 PRECONSTRUCTION TESTS

When formulating a mix, the first step is to estimate the ingredients and dosages, based on experience and initial calculations. The compatibility and performance of the components should be tested at this point. Table 5 shows tests on components recommended by Austrian Guideline – Sprayed Concrete 2013.

The second part of pre-construction testing aims to identify the best mix, as batched and sprayed, using similar equipment to that which will be used during the actual production. This part of the test programme culminates in the qualification process, which is the official test to confirm the approved mix for construction.

Table 6 shows the recommended preconstruction tests on properties and composition of the sprayed concrete, according to EN 14487-1. Depending on other project-specific requirements,

Table 6 : Preconstruction tests (after Table 9, EN 14487-1)
 a Only for fibre reinforced sprayed concrete
 b Residual strength or Energy Absorption Capacity can be specified

PRODUCT TEST LEVEL	TESTS AS PART OF THE PRECONSTRUCTION TEST OF THE SPRAYED CONCRETE BY AN ACCREDITED BODY	SUITABILITY VERIFICATION	
Cement	<ul style="list-style-type: none"> • 1 d compression strength • Blaine value 	Current test report of the third-party monitor of the production plant	Certificate of the plant's production control, incl. annex
Addition	<ul style="list-style-type: none"> • Specific surface¹ 		
Accelerator (EB)	<ul style="list-style-type: none"> • Setting times² • Density • PH value • Solid material content • Storage stability 	Producer declaration Initial verification ³	
Superplasticiser (FM)	<ul style="list-style-type: none"> • Verification as part of the mix test (consistency and air void content via the processing time) 		
Aggregates	<ul style="list-style-type: none"> • Grading curve of the individual grain fraction • Fines content • Freeze / thaw resistance⁴ • CO₂ content⁵ 		
Fibres	<ul style="list-style-type: none"> • Dimensions of the fibres • Humidity 	Initial test of the product by accredited body	

Table 5 : Tests on components from Austrian Guideline – Sprayed Concrete 2013
 1 For fly ash, AHWZ in accordance with ÖNORM EN 196-6 and for silicafume in accordance with ISO 9277
 2 With cement used with and without HRWR agent
 3 incl. the additional requirements of this directive for the product standard
 4 Only in the event of frost or freeze/thaw-resistant sprayed concrete without valid test verification
 5 Only in the event of the XA2L requirement for the sprayed concrete without valid test verification
 6 Only in the event of polymer micro fibres

TYPE OF WORK	STRENGTHENING OF THE GROUND
Inspection category (as per EN 14487-1)	3
PROPERTY	
Consistency of the wet mix	To be done
Early age strength development	To be done
Compressive strength	To be done
Modulus of elasticity	Optional
Bond to substrate	Optional
Ultimate flexural strength	To be done
First peak flexural strength^a	To be done
Residual strength^{a, b}	To be done
Energy absorption capacity^{a, b}	To be done
Freeze/thaw resistance (with or without de-icing salts)	If applicable
Resistance to water penetration	If applicable
COMPOSITION	
Fibre content^a	To be done
Maximum chloride content	If applicable

additional tests may be needed, such as tests on durability and shrinkage (see 14.7). It is essential that pre-construction testing is completed in good time before construction starts so that the mix design can be finalised to demonstrate that it fulfils all aspects of the design requirements.

14.2 TESTING DURING CONSTRUCTION

As with normal concrete, a range of quality control tests are performed to demonstrate that the concrete sprayed complies with the specified requirements. Table 7 shows the recommended tests on parameters of the sprayed concrete during construction, after EN 14487-1.

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. In addition to this, tests are required on the components and the fresh mix (e.g. see EN 14487-1 Tables 10 & 11), along with the test methods for each test. Depending on other project specific requirement, additional tests, such as durability, may be needed.

The frequency of tests can vary depending on the results. If positive results are consistently achieved, the frequency of some tests can be relaxed. If, after this, negative results occur, the original frequency is re-established.

14.3 ACCELERATORS

The components of sprayed concrete are largely the same as the components of normal concrete, with the exception of the accelerator. Accelerators can present significant health and safety risks so only non-caustic, low-alkali accelerators should be used (i.e. < 1% equivalent Sodium Oxide (Na₂O) content). The function of the accelerator is checked with setting time tests.

The long-term strength of accelerated mixes will be reduced compared to unaccelerated ones. In some standards a 'maximum strength

TYPE OF TEST	METHOD	INSPECTION CATEGORY 3
CONTROL OF FRESH CONCRETE		
1 Water / binder (w/c) ratio Workability	By calculation or test method Slump or flow table	Daily
2 Accelerator	From quantity added	Recommended every batch
3 Fibre content	EN 14488-7	1/100 m ³ or 1/500 m ²
CONTROL OF HARDENED CONCRETE		
4 Early age strength	EN 14488-2	1/1250 m ² or twice per month
5 Compressive strength	EN 12504-1	1/250 m ³ or 1/1250 m ²
6 Density	EN 12390-7	1/1250 m ²
7 Bond strength	EN 14488-4	1/1250 m ²
CONTROL OF FIBRE REINFORCED CONCRETE		
8 Residual flexural tensile strength or energy absorption capacity	EN 14651, EN 14488-5 or ASTM C1550	1/100 m ³ or 1/500 m ²
9 Ultimate flexural strength	EN 14651	Recorded when testing residual flexural tensile strength
10 First peak flexural strength	EN 14651	
Fibre content can be measured when testing residual strength if not done already.		

Table 7 : Quality control tests & minimum recommended frequencies (after Table 12, EN 14487-1)

loss' of accelerated versus unaccelerated samples is defined and would therefore require additional preconstruction testing. However, test results comparing accelerated and unaccelerated mixes are often unclear, and hence the tests are very rarely carried out.

With modern accelerators, the strength difference between accelerated and unaccelerated mixes is usually small. It is best to focus on the achieved strengths (compared to the design requirements) and other durability parameters to ensure the desired final quality.

14.4 LONG-TERM STRENGTH

For convenience, conventional targets

for concrete strength are set at an age of 28 days. However, concrete continues to hydrate over a longer period, particularly if cement replacements are used. Therefore, the strength and density tend to increase after 28 days. Often sprayed concrete mixes contain such high quantities of binders to achieve early age strength targets that they overshoot the 28-day strength target and are much stronger than needed in the long-term.

Bearing this in mind, it may be worth considering setting lower targets for the strength of PSCL at 28 days and including some tests at 56 days to check that the desired strength target is met in the long-term. This offers more freedom to adjust the mix design for permanent applications.

14.5 TESTS ON STRUCTURAL FIBRES

Testing the performance of structural fibres is a specialist area but since fibres are very often used in PSCL, some additional comments have been included here. The main tests related to fibres are:

- Fibre content.
- Energy absorption capacity.
- Residual flexural tensile strength, for example by:
 - Three point bending test with notch.
 - Four point bending test on round panel.

Chapter 18 (Appendix 4) contains an overview of the residual strength and energy absorption (i.e. toughness) tests for fibre-reinforced sprayed concrete with some brief comments. The type of tests required depends in part on which parameters are used in the design. For example, energy absorption is often specified for the design of hard rock tunnels.

14.6 Test methods

The case of a PSCL essentially follows the normal procedure for sprayed concrete but there may be some additional requirements due to the fact it is a permanent structure. Some of the guidance advocates different levels of testing, depending on the purpose of the structure. For example, EN 14487-1 contains categories of which Category 3 is relevant for PSCL.

Table 8 lists the standards which contain test methods needed for PSCL, for Europe, USA and Japan. The best approach is to follow, as far as possible, one of these groups of standards rather than picking test methods randomly from different groups. This will provide a consistent testing regime which is easier to enforce and to align with the design requirements. These standards also recommend how to deal with non-conformances.

TEST METHODS	EUROPE	USA	JAPAN
TEST ON COMPONENTS			
Cement	EN 206-1, EN 197-1	ASTM C150	JIS R 5210
Aggregates	EN 12620	ASTM C33	JIS A 5005
Admixture	EN 934-2	ASTM C494M	JIS A 6204
Fibres	EN 14889-1 & 2	ASTM A820/ C1116	
Accelerator	EN 934-2		JSCE-D 102
TEST ON FRESH CONCRETE			
Consistency	EN 12350-2	ASTM C143	JIS A 1101
Air content	EN 12350-2	ASTM C231	JIS A 1128
Specific gravity	EN 12350-2	ASTM C138	JIS A 1116
TEST ON HARDENED CONCRETE			
Strength test on young sprayed concrete	EN 14488-2		JSCE-G561
Compressive strength	EN 12504-1	ACI 506.2-13, ASTM C1604 /C1604M	JSCE-G562
TEST ON FIBRES - HARDENED CONCRETE			
Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel)		ASTM C1550 ASTM C1550	
Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete		ASTM C1609	JSCE-G552
Testing sprayed concrete - Part 5: Determination of energy absorption capacity of fibre reinforced slab specimens.	EN 14488-5		
Test method for metallic fibered concrete - Measuring the flexural tensile strength	EN 14651		JSCE-G552
Method of Tests for Flexural Strength and Flexural Toughness of Steel Fibre Reinforced Concrete.			JSCE-G552

Table 8 : Common test methods for sprayed concrete in Europe, USA & Japan

14.7 Durability testing

For conventional concrete, strength, density and permeability are typically taken as indicators of the potential durability of concrete, although permeability is not usually tested regularly. Recommendations for the frequency of testing for these parameters can be found in standards such as EN 14487-1, Table 12. The typical limit on water penetration, tested according to EN 12390-8, is less than 50 mm but some projects have set tighter limits, e.g. 25 mm (Crossrail, UK). Water penetration tests are only an empirical measure of concrete permeability, but this is adequate. If the lining may be exposed to freeze-thaw conditions, the resistance of the concrete to freeze-thaw should also be checked (e.g. see ACI 506R-16 2016 and NB 7 2011, 2021).

The samples for checking durability should be taken from locations that are representative of the entire lining, which means cores should be taken from all parts of the lining including locations which are harder to spray, such as the crown. Core holes in the lining should be filled with non-shrink mortar afterwards.

Any requirements for durability testing, such as water penetration or permeability, sorptivity or chloride diffusion should be conducted during pre-construction trials with the chosen mix design for compliance. The repeated use of these tests for Quality Control purposes during the construction phase can be expensive and time consuming. It can be argued that, in modern day computerized batching plants, it is possible to have real time quality control on the batched concrete by the automatic monitoring of batch weights and ensuring the proportions of the compliant mix design are all within accepted batch weight tolerances as per the relevant standards

and guidelines. Hence additional durability tests are not needed, as long as the mix is not changed. This is complemented by the strength testing on insitu samples which demonstrates that the concrete has been correctly applied.

Permeability tests tend to be time-consuming to perform which has led to suggestions of simpler tests to assess the durability of sprayed concrete such as measuring Permeable Voids, Boiled Absorption or Rapid Chloride Permeability, (Morgan 1994, ASTM C642-13 & ASTM 1202). However, it is very difficult to relate these tests directly to the processes that might compromise durability. While used routinely in some places like North America, these tests are only indirect indications of quality.

Over the last decades a large number of tunnel projects have successfully used permanent sprayed concrete linings, out of which 151 projects covering 520 km of tunnels are described by Franzén et al. (2001). A few countries are represented in this record with many reference cases, namely the Czech Republic with mainly utility tunnels, Norway with road tunnels, Sweden with road, rail and utility tunnels, and Switzerland with rail, utility and hydropower tunnels.

The period from 2001 to 2020 has seen an increasing use of PSCL, but also a trend to stricter functional requirements on waterproofing as well as an increased focus on long term durability.

In Scandinavian countries permanent sprayed concrete was already the standard around 1990. However, the final inner waterproof lining in traffic tunnels in hard rock was constructed with a drainage shield structure. In Norway alone, more than 1000 km of railroad and highway tunnels were built from 2001 – 2019 using sprayed concrete as a final rock support lining (Norwegian Tunnelling Association, 2019).

The Table 9 lists the selected references.

	PROJECT	COUNTRY	TYPE	YEAR OF COMPLETION	AREA OF USE	GROUND
1	Vereina	Switzerland	Rail	1999	Final lining	Rock
2	Hindhead	United Kingdom	Road	2009	Final lining	Soil
3	Gevingås	Norway	Rail	2011	Final lining	Rock
4	Elizabeth Line	United Kingdom	Rail	2015	Final lining	Soil
5	Rivaloro	Italy	Road	2015	Final lining	Rock
6	Strathfield	Australia	Rail	2015	Final lining	Rock
7	Seymour Capilano	North America	Water	2015	Final lining	Rock
8	Serra do Cafezal	Brazil	Road	2017	Final lining	Rock/soil
9	Chuquicamata	Chile	Mining	2018	Final lining	Rock
10	Kingsgrove Ramps	Australia	Road	2020	Final lining	Rock

Table 9 : Selected project references

15.1 VEREINA, SWITZERLAND

15.1.1 Project Details

History & brief description :

The Vereina Tunnel is a railway tunnel, and the principal part of the Vereina railway line, in the canton of Graubünden, eastern Switzerland. At 19,058 meters in length, the Vereina Tunnel is the longest tunnel on the Swiss Rhaetian Railway (RhB) network as well as the world's longest narrow gauge railway tunnel.

The tunnel was built to improve all-weather transport links in the eastern part of Canton Graubünden, as the Flüela Pass (between Davos and Susch) is prone to heavy snowfall and avalanches in winter. Construction began in 1991 and the tunnel opened to traffic in November 1999. The total cost of the tunnel came to CHF 812 million. The tunnel is single track, with passing loops (each 2 km long) in the middle and near the two portals.

The excavation of the tunnel was done from the north with a tunnel boring machine (TBM) and from the south by conventional drill-and-blast method. The breakthrough happened sooner and at a more northerly point than expected on 26th March 1997 because the rock quality on the southern side was unexpectedly good and so the excavation was faster.

Year : 1991-1999.

Client and Location :

Rhb, Rhaetian Railway.

Type of tunnel : Narrow-gauge railway single-track tunnel (1000 mm).

Ground conditions : Rock.

Alignment length : 19,058 m.

Depth : max. overburden: 1,500 m.

Excavation : From the south by full face drill and blast with variable cross section. The drill and blast construction was optimized by the use of a suspended back-up system, allowing high advance rates. The

northern part of the tunnel was excavated by a hard rock open face TBM, Ø 7.64 m.

15.1.2 Design Approach Adopted

Design method : The rock support was done using fully resin grouted fiberglass rock-bolts, wire mesh and sprayed concrete. Water inflow was captured by drainage layers and half pipes directly applied on the rock or the first sprayed concrete layer. Finally, a permanent sprayed concrete lining was applied reinforced by wire mesh. The lining thickness varies throughout the tunnel depending on the corresponding rock load.

Lining thickness : Primary lining = 50 mm to 200 mm (depending on geology); Secondary lining = 100 mm to 150 mm.

Inner and outer diameter :

ID ~7 m; OD 7.6 m.

Quantity of fibers per m³ of concrete :

Fibers were not common at this time and therefore only partly used in the project (45-50 kg/m³ steel fibers).

Waterproofing :

A systematic drainage network guarantees the control of water inflow. Wet surfaces were covered by a drainage sheet and collected by the use of halfpipe flexible drains. Spot water inflows were also collected and all the halfpipes then connected to the longitudinal tunnel drainage pipe. There is no waterproofing layer apart from the high quality sprayed concrete.

15.1.3 Project key points

Sprayed concrete was applied in thin layers to guarantee a high quality compaction.

- The substrate was washed carefully before the application of the next layer to achieve the best bonding performance
- The watertightness is achieved by systematic drainage and collection of water inflow. No waterproofing layer (membrane) was applied.

Typical lining mix design :

COMPONENT	QUANTITY (Kg/m³)
Cementitious binder	400-450
Microsilica	20

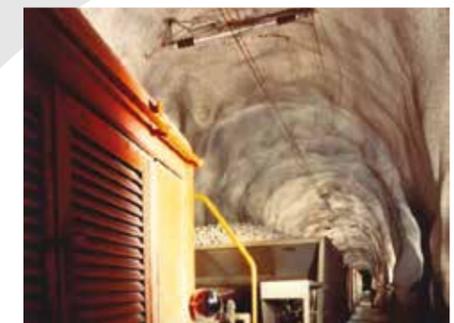
15.1.4 Picture Reference



Vereina tunnel, intersection portal zone.



Vereina tunnel, single-track TBM section.



Vereina tunnel, single-track D&B section.

15.2 HINDHEAD, UNITED KINGDOM

15.2.1 Project Details

History & brief description :

The Hindhead project includes twin two lane road tunnels under an area of environmental importance in the south of England. The ground was a weak sandstone with up to 20% interbedded soil layers. The stable ground and its relatively dry condition (since it is above the water table) allowed the use of a permanent sprayed concrete lining. This made a significant saving in cost and programme compared to the traditional design approach. This is the first road tunnel in the UK with a permanent sprayed concrete lining.

Year : 2007-2009.

Client and Location : Highways Agency, UK.

Type of tunnel : Twin bore road tunnels.

Ground conditions :

Sandstone of the Hythe Beds, mostly above the measured water table.

Alignment length : 1830 m.

Depth : Cover varies significantly, reaching a maximum of 65 m.

Excavation :

Mechanical diggers (Liebherr 944 diggers). Sandvik Tamrock Axera 8 rigs, (for ground probing and installing the 4 m long, 32mm diameter, self-drilling, GFRP dowels & spiles).

1.79 km of the tunnel was mined, while there was also 30 m of cut and cover tunnel at either end.

15.2.2 Design Approach Adopted

Design method : The primary lining is fibre reinforced permanent sprayed concrete. For this lining to be permanent, as far as possible steel bars were avoided. Hence there were no lattice girders or steel mesh. A limited amount of bar reinforcement

was installed at the junctions for cross-passages.

While the designers considered a composite lining approach, in the end they opted for designing the primary lining to carry all ground and water loads. The 150 mm secondary sprayed concrete lining is non-structural with the purpose of protecting the spray applied waterproofing membrane, the aesthetic finish and carrying minor loads for fixings. Heavy equipment such as the jet fans is supported on pre-drilled anchors which extend through the linings and which were sealed by spraying the waterproofing membrane around the bolts.

Sprayed concrete strength :

- C32/40 (J2 early age strength after BS EN 14487-1 and energy absorption of > 700 Joules).
- Water penetration < 50 mm.

Lining thickness : Primary lining = 200 mm to 300 mm (where there is overbreak); Secondary lining = 150 mm.

Inner and outer diameter :

ID ~11 m; OD 11.6 m.

Quantity of fibres per m³ of sprayed concrete :

30 kg/m³ of steel fibres or 6 kg/m³ of macrosynthetic fibres.

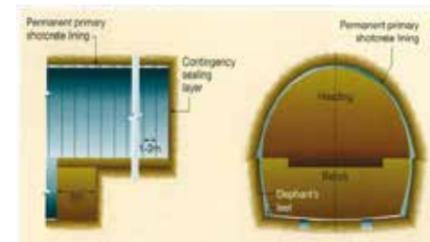
Typical secondary lining mix design :

COMPONENT	QUANTITY
Cement	390 kg/m ³
Fly ash	50 kg/m ³
Microsilica	50 kg/m ³
Plasticiser	2.8 l/m ³
Stabilizer	2.5 l/m ³
Accelerator	7 %
Water/binder	0.38

15.2.3 Project key points

- The permanent SCL was applied in progressive layers to the crown and walls, and as a single mass for the elephant's feet to avoid the risk of rebound entrapment or lamination.
- The permanent SCL was made watertight by adding a spray-applied waterproofing membrane.
- The main extra support used in the fault zones were GFRP dowels combined with face sealing sprayed concrete.
- Spiles were also sometimes used and it was shown that spiles could be drilled without the benefit of a lattice girder to guide their positioning.
- At the south end, a heavier, pipe canopy installation was applied, consisting of arrays of 140mm diameter, 12m long circular steel pipes. With the canopy in place, the heading could advance approximately 8m before a new round of pipes was installed.
- Rising steel prices led the contractor to switch from steel fibres to using macrosynthetic fibres.
- In the case of any fire, the structural primary lining is protected by the secondary lining which has microfine polypropylene fibres in the concrete mix which would melt at high temperatures and allow the water or water vapour to expand and reduce damage.
- Cast insitu side walls were used for part of the secondary lining to give a good reflectance of the lighting in the road tunnel. The crown was sprayed PSCL.

15.2.4 Picture Reference



Heading and bench excavation sequence.

15.3 GEVINGÅS, NORWAY

15.3.1 Project Details

History & brief description :

The Gevingås railway tunnel was constructed as a modernization of the oldest parts of the Nordland rail line between Trondheim and Bodø.

Year : 2009 - 2011.

Client and Location :

Owner: Norwegian National Railroad Administration, region north, Trondheim, Norway.

Type of tunnel : Single track, without electrical power line. For diesel powered trains.

Ground conditions : Jointed hard rock of fair to good quality, with meta sandstones, meta shales. Uniaxial compressive strength: 120-150 MPa. Young's modulus intact rock: 45-50 GPa.

Alignment length : 4100 m.

Depth : 30 – 120 m rock overburden.

15.3.2 Design Approach Adopted

Design method : Rock support design according to Norwegian hard rock approach, utilizing the Q-system for rock mass classification and rock support. Original design and inner lining with traditional Norwegian drainage and thermal insulation system. Final design: Central part, 1850 linear meters with innovative system with bonded spray-applied water proofing in combination with permanent sprayed concrete inner lining. 1100 m on either side from the portals: Traditional PU-foam and sprayed concrete drainage and thermal insulation lining.

Lining thickness : Primary lining rock support sprayed concrete: 70-100 mm Secondary lining : 60 mm.

Sprayed concrete mix design, primary and secondary :

Cement : CEMII 42,5 A-V, 513 kg/m³ (Norcem Standard FA Flyash cement)
Silica fume densified 21 kg/m³
w/b ratio: 0,44 (inclusive of w added at nozzle through accelerator)
Aggregates 0-4 mm : 343 kg/m³
Aggregates 0-10 mm : 1245 kg/m³
Fibres, structural PP : 6 kg/m³.

Observed cracking of concrete in final condition:

Minor cracking observed as expected, not posing any detrimental effects or needs for maintenance.

Typically measured crack apertures: 0.1 to 0.4 mm in sprayed concrete inner lining applied onto bonded membrane (partly restrained sprayed concrete).

Inner lining sprayed concrete applied on PE-foam sheets: Every 10 m : one circumferential crack with approximately 5 mm crack width in a deliberately induced crack at intended location.

15.3.3 Project key points

- Original design was based on traditional Norwegian method with drainage lining based on PE-Foam and fire-protection sprayed concrete.
- Ground conditions and water seepage situation were favorable for spray-applied waterproofing.
- Final lining design was reconsidered for the central part of the tunnel comprising 1850 linear m of a total of 4100 m using an innovative sprayed concrete based lining system.
- Technically successful and cost-effective result with the innovative final lining system based on bonded spray applied waterproofing in combination with sprayed concrete.

15.3.4 Picture Reference



Central portion of the 4100 m long Gevingås railroad tunnel in central Norway, with permanent sprayed concrete and bonded spray-applied waterproofing membrane.

15.4 ELIZABETH LINE, UNITED KINGDOM

15.4.1 Project Details

History & brief description :

The Elizabeth Line is a new railway, passing east-west underground through the heart of London. Formerly known as Crossrail, this is vital link in the commuter rail network. PSCL is used widely on this project.

The PSCL tunnels include:

- All station tunnels / adits at Bond Street, Tottenham Court Road, Farringdon, Liverpool Street Station, and Whitechapel.
- All intermediate shafts, crossovers and cross passages (Stepney Green Crossover, Whitechapel Crossover, Eleanor Street, Mile End, and Limmo)

Further information can be found at : learninglegacy.crossrail.co.uk.

Year : 2012 - 2017.

Client and Location :

Crossrail Ltd, UK.

Type of tunnel : Railway tunnels, Station tunnels and caverns.

Ground conditions :

Soft ground (London Clay & other equally low permeability strata) / Sand channels and laminated beds in the Lambeth Group.

Alignment length :

approx. 14 km of station and tunnels; Depth - up to 40 m.

15.4.2 Design Approach Adopted

The permanent primary lining was designed to take the full short-term applied ground load and any other loads, during the two years prior to secondary lining installation.

The primary lining consists of a sprayed concrete lining containing structural steel fibres, which increase the concrete's ductility and provide post crack tensile resistance.

- Long term ground pressure (a portion of this was carried by the primary lining)

- Internal loads (mechanical / electrical equipment)
- Temperature and shrinkage

The secondary linings contain micro-synthetic fibres (typically 1 kg/m³) to limit the explosive spalling and maintain structural integrity in case of a fire.

The overall design life is 120 years. Apart from the strength requirement and normal concrete mix design, other criteria included: the mean water penetration of less than 25 mm for the primary lining, shrinkage less than 0.03% and the water-cement ratio less than 0.45.

A spray applied waterproofing membrane was installed between the primary and secondary lining of all SCL tunnels (except Farringdon and tunnels in the Lambeth Group), to provide a waterproof lining.

These were significant innovations at the time and enabled the elimination of almost all of the steel bar reinforcement in the linings. This was the first large scale use of PSCL and spray applied waterproofing membranes on the London Underground.

Construction sequence :

SPAN	DESCRIPTION	CROSSRAIL TUNNELS
Up to 5m	Full face	Service Tunnel
		Temporary access/ construction tunnels
5 to 9m	Top heading, bench, invert (May include temporary invert strut in top heading)	Running tunnel cross passages
		Station cross Passages
		Ventilation Tunnels
		Escalator tunnels
9 to 13m	Pilot-enlarge-ment	Platform Tunnels
		Concourse Tunnels
12 to 14m	Single sidewall drift	Fisher Street and Step-ney Green tunnels
14 to 18m	Double sidewall drift	Stepney Green

Sprayed concrete strength:

C 32/40 with a flexural tensile strength of D1 S1.8 (after BS EN 14487-1).

Lining thickness: for a 10 m diameter tunnel, the primary lining was typically 325 mm (excluding the sacrificial layer) and the secondary was 400 mm thick.

15.4.3 Project key points

- Design was based on moderately conservative ground parameters.
- Permanent sprayed primary linings incorporate steel fibre reinforcement. The external 75 mm of the lining considered to be sacrificial in the long term.
- The primary sprayed concrete forms part of the permanent lining at junctions where it incorporated standard steel reinforcement.
- Excavation face sizes were based on experience and stability calculations. Where large tunnels were required, and the geometry was appropriate, pilot tunnel construction sequences were used to provide suitably sized headings.
- Modern target-less laser scanning and surveying techniques were used to eliminate the requirement for lattice girders for profile control in tunnels.
- Sprayed secondary linings were installed with a sprayed waterproof membrane.
- Junctions were designed so that the bar reinforcement could be installed safely within an enlarged section of the fibre reinforced primary lining.

Typical secondary lining mix design:

COMPONENT	QUANTITY (Kg)
CEM I cement	419
Limestone aggregate	860
Marine sand	860
Microsilica	54
Plasticiser	71
Water	162

15.5 RIVAROLO, ITALY

15.5.1 Project Details

History & brief description :

Rivarolo tunnel is an highway tunnel on the A12 highway which is one of the main connections between Milan and Genoa. A12 highway has been opened to traffic on 1935 it is now daily crossed by more than 30'000 vehicles per day.

The excavation of the tunnel has been carried out with the use of D&B technology. The original project expected to line with cast in situ concrete some portions of the tunnel, the remaining parts where shotcreted without waterproofing.

Autostrade per l'Italia decided to improve the unlined portions adopting a spray applied waterproofing and concreting, with the aim of completing the whole operation without installing temporary scaffolds since the tunnel must be kept open during day time. This approach allowed to complete the job during night shifts with minor impact on transits.

Year : 2015.

Client and Location :

Autostrade per l'Italia – Genoa (Italy).

Type of tunnel : Two lines highway tunnel.

Ground conditions : Rock.

Alignment length : 641 m.

Depth : max. overburden: 10-100 m.

Tunnel lining conditions :

The tunnel was partially lined with a cast in situ concrete, another portion was unlined with a shotcrete layer on top.

The first portion is in good conditions without need of any kind of refurbishment, whereas

the shotcreted part was facing seepage for which is has been necessary to waterproof and line at the same time.

15.5.2 Design Approach Adopted

Design method : The existing shotcrete was washed with high pressure waterjet in order to remove the dirt layers; some portion where slightly milled with a roadheader to remove carbonated portions especially where water was flowing inside. Water was drained at the bottom of the tunnel with half pipes or with PVC coupled with geotextile. Following step was to spray a smoothing layer to get an homogeneous support on top of which the spray applied waterproofing layer was put in place, after having installed fully resin grouted anchors.

Final step was to install wire mesh anchored to the waterproofed substrate and then spraying on top high quality shotcrete, with a thickness between 100-150 mm.

Lining thickness :

Primary lining = 300 mm to 600 mm (depending on geology); Secondary lining = 100 mm to 150 mm

Inner and outer diameter :

ID ~11 m

Waterproofing :

For both casted in situ and shotcreted portion, PVC sheet where not installed. Now the shotcreted portion has a spray applied waterproofing layer.

15.5.3 Project key points

Sprayed concrete was applied with a robotic and automatic equipment to guarantee a constant and high quality shotcrete layer.

- The presence of a waterproofing layer enhances the durability of the shotcrete layer
- Shotcreting gave the chance of closing the tunnel overnight only.

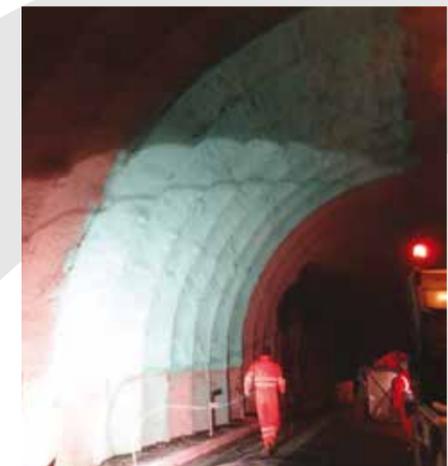
Typical secondary lining mix design :

COMPONENT	QUANTITY
CEM II cement	480 kg
Sand 0-3mm	1120 kg
Aggregate 3-9mm	480 kg
Silica Fume	30 kg
Plasticiser	5.8 l
Water	206 kg

15.5.4 Picture Reference



Rivarolo tunnel, top view of the existing tunnel.



Rivarolo tunnel, application of the spray applied waterproofing layer.

15.6 STRATHFIELD, AUSTRALIA

15.6.1 Project Details

History & brief description :

The North Strathfield Rail Underpass tunnel in Sydney, Australia, is a 148 m rail tunnel built for freight trains up to 1.5 km in length. While short, the tunnel is technically complex. The 9 m wide, arched roof twin tunnels were excavated by road header underneath operational passenger rail lines with a maximum overburden of 3 m.

Year : 2014-2015

Client and Location :

Sydney City, Sydney, Australia.

Project Team :

NSRU Alliance (Transport for NSW, John Holland and Bouygues). The lead designers were the JV of SKM and PB with Mott MacDonald being the designer of the driven tunnel presented here.

Type of tunnel : Freight rail tunnel.

Ground conditions :

Stiff Clay, Weathered Shale and Dark grey shale rock intersected by a dyke of stiff clay.

Tunnel Dimensions :

148 m in length and 9 m wide.

Depth : maximum 3 m.

15.6.2 Design Approach Adopted

Design method : The permanent ground support in the tunnel consists of a 250 mm thick macro synthetic fibre reinforced single pass wet mix sprayed concrete lining. No steel sets or lattice girders were used. The design is based on an arched profile ensuring that the sprayed concrete itself is always in compression under both dead and live loading. A 100 mm fire protection layer was applied over a waterproofing membrane with 2 kg/m³ of micro synthetic fibres to withstand a 4-hour hydrocarbon fire. FE Analysis showed a maximum compressive strength of approximately

4 MPa (dead load plus live load). The sprayed concrete was required to gain a strength of 6 MPa before the next excavation cycle could commence. Following pre-production trials with various types of fibres, a dosage of 6 kg/m³ of macro synthetic fibres was selected as the reinforcement. Table 1 shows the sprayed concrete mix design.

Sprayed Concrete Mix Design :

MATERIAL	PROPORTION (Kg/m ³)
Cement	370
Fly Ash	100
Silica Fume	30
10 mm	520
Sand	1100
Superplasticiser	4.8
Macro Synthetic Fibre	6
w/b ratio	0.43

Sprayed concrete strength : Primary & secondary lining 40 MPa, and minimum 6 MPa before next cycle.

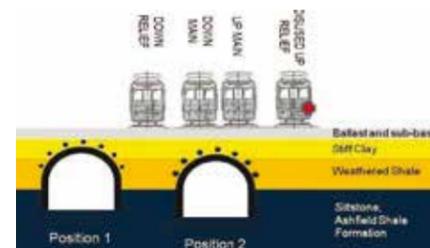
Lining thickness : Primary lining = 250 mm with 6 kg/m³ of macro synthetic fibres; Secondary lining = 100 mm with 2 kg/m³ of micro polypropylene fibres for fire resistance.

15.6.3 Project key points

The macro synthetic fibres in the structural sprayed concrete lining served four main functions:

1. To reduce shrinkage cracking widths in the sprayed concrete if they occur.
2. To provide residual strength and distribute load within the lining should the sprayed concrete crack due to some unknown flexural force or ground movement.
3. Increase speed of excavation.
4. Improve sprayed concrete durability over the 100-year life of the tunnel.

15.6.4 Picture Reference



Tunnel alignment under active commuter rail lines.



800 mm wide dyke in the tunnel face.



Applied macro synthetic fibre reinforced sprayed concrete in the driven tunnel.

15.7 SEYMOUR CAPILANO, NORTH AMERICA

15.7.1 Project Details

History & brief description :

This project is a key element in the water supply to Vancouver in Canada. Two tunnels, deep beneath Grouse Mountain and Mount Fromme, convey water from the Capilano Reservoir to the new Seymour-Capilano Filtration Plant, before being returned to the Capilano system for distribution.

The tunnels are 3.8 m in diameter and 7.1 km in length, with 4.0 m diameter, raise-bored shafts up to 275 m deep at either end. The tunnels were excavated using hard rock tunnel boring machines. The permanent rock support consists of rockbolts and sprayed concrete. The shafts also have a steel lining for watertightness which extends into the start of the tunnels.

Designing in mountainous terrain with rock cover up to 640 m the permanent rock support in many sections relies on sprayed concrete acting in concert with rock bolts.

Year : 2005 – 2015.

Client and Location :

Metro Vancouver, Canada.

Type of tunnel :

Water supply tunnel.

Ground conditions :

Granite, with a minimum of 50 m rock cover to overlying glacial soils; strengths ranging from 35 MPa to 260 MPa; rockburst encountered in areas with the highest overburden.

Alignment length : 7100 m.

Depth : up to 640 m.

15.7.2 Design Approach Adopted

Design method :

The majority of the length of the tunnels is either unlined or it has a permanent sprayed concrete lining. To avoid water flowing between the tunnels, there is a minimum of 100 m between the two tunnels in unlined sections. By reducing the extent of the steel lining by 10 km, the cost of the project was reduced by \$40 million.

Some post-grouting with cementitious grout was required to fill voids in the rock mass. This was carefully monitored and controlled to ensure that the lining was not damaged during grouting.

Lining thickness :

- Class II support (4 < Q < 10)
Spot bolting with locally applied 50 mm of sprayed concrete, as required; mesh added if needed.
- Class IV support (0.1 < Q < 1)
Pattern rock bolting in the crown with a full ring of 75 mm of mesh reinforced sprayed concrete.

Nominal diameter : 3.8 m

Quantity of fibres per m³ of concrete : zero – steel mesh reinforcement

Mix design : not known

15.7.3 Project key points

- All materials used had to be conform with drinking water safety standards.
- The tunnels and shafts have been designed to cope with maximum credible earthquake, according to the local seismic design codes.
- The extent of the steel lining was minimized whilst safeguarding against adverse interaction between the internal water pressure and the external groundwater.
- 3D numerical models were used in the design of the junctions and chambers at the shafts in the highly stressed rock mass.
- Computational Fluid Dynamics (CFD) was used to design the rock traps.

15.7.4 Picture Reference



Excavation of a rock trap



Installation of the rock support in a rock trap

15.8 SERRA DO CAFEZAL, BRAZIL

15.8.1 Project Details

History & brief description :

The four tunnels of the Serra do Cafezal Project are road tunnels, and part of a big highway project, which also includes thirty-nine bridges. This project intends to make the trip from São Paulo to the South of Brazil, on the Regis Bittencourt Road faster and safer. It starts in São Paulo and passes through eleven cities in São Paulo State, and in five cities in Paraná State, until it reaches Curitiba. The whole length of the road is 402 km, used by more than 127 thousand vehicles per day. The total project cost is 1.3 billion Brazilian Real.

Year : 2010-2017.

Client and Location :

Autopistas Regis Bittencourt (Arteris Group), São Paulo, Brazil.

Project Team :

NSRU Alliance (Transport for NSW, John Holland and Bouygues). The lead designers were the JV of SKM and PB with Mott MacDonald being the designer of the driven tunnel presented here.

Type of tunnel : Road tunnels: T1, T2 and T3: three lanes, T4: four lanes.

Ground conditions :

Gneiss rock, residual gneiss soils, altered gneisses rock, landfill sites.

Alignment length :

T1: 346 m; T2: 231 m; T3: 741 m; T4: 415.

Depth : max. overburden: T1: 80 m; T2: 70 m; T3: 85 m; T4: 85 m.

Excavation : Full face drill and blast with variable cross section and NATM method.

15.8.2 Design Approach Adopted

Design method : Because of the very steep natural slopes, the design of the ground support was challenging.

For example, using extremely robust false tunnels to withstand the ground pressures. In the tunnels, the rock support was done with resin grouted rock-bolts, wire mesh and sprayed concrete. Water inflow was not very high and it was captured by drainage layers. A permanent sprayed concrete lining was applied, reinforced by wire mesh.

Lining thickness : Primary lining = 250 mm to 300 mm (45 MPa at 28 days; Secondary lining = 200 mm to 250 mm (60 MPa at 28 days); Fire protection layer = 60 mm

Inner and outer diameter :

T1, T2, T3: ID ~ 11,5 m; OD 19.0 m, T4: ID ~14,4 m; OD 23.3 m

Quantity of fibers per m³ of concrete :
Polypropylene fibres for the fire protection layer: 2,0 kg/m³

Waterproofing :

Isolated water inflows were captured by drainage layers and drains, which were applied between the primary and the secondary linings. Crystallizing admixtures were used on the secondary lining, in order to avoid new water inflows. No waterproofing membrane layer was applied.

Primary lining mix design :

COMPONENT	QUANTITY (Kg)
Sulphate resisting cement	443
Aggregate	844
Rock sand	307
Natural sand	530
Specialist admixtur	1.86
Plasticiser	2.66
Water	195

15.8.3 Project key points

Sprayed concrete for both the primary and secondary linings are designed to be permanent. The mix design of the secondary lining included crystallizing admixtures in order to avoid new water inflows. A fireproofing lining was also used with good results.

15.8.4 Picture Reference



Serra do Cafezal T2, sprayed concrete lining.



Serra do Cafezal T3, aerial view.

15.9 CHUQUICAMATA, CHILE

15.9.1 Project Details

History & brief description :

Chuquicamata Underground mine is a structural and strategic project that represents an important part of Codelco's future and consists of the transformation of the largest open pit in the world into a giant underground operation. This will exploit the new reserves through a underground mine, which will be one of the largest, most modern and efficient in the world.

Year : 2012-2018.

Client and Location :

Codelco Chuquicamata division, Calama región Antofagasta.

Type of tunnel :

Infrastructure & main ventilation tunnels.

Ground conditions :

Amphidorite rock and diorite.

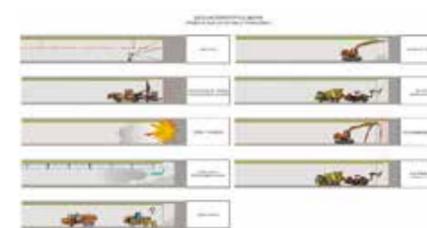
Alignment length :

25 km of horizontal developments sloping down at 14.6° and 700 meters of vertical shaft.

Depth : cover of up to 1050 meters.

Construction sequence :

Full fase drill and blast.



15.9.2 Design Approach Adopted

Design method :

The tunnel lining was designed for the operation of the main ventilation system of the underground mine (duration 50 years).

Depending on the support class, the lining consists of support by 30 MPa sprayed concrete, macrosynthetic fibres, welded wire steel mesh, helical A-420 steel bolts, cable bolts and steel arches.

Lining thickness :

First, a sealing coat of 50 to 70 mm is sprayed, depending on the rock class. The final thickness varies from 100 mm in Class CS1 to 400 mm in Class CS5.

Inner and outer diameter :

Internal diameter = 8 m; external diameter = 8.05 to 8.40 m.

Quantity of fibres per m³ of concrete :

4 kg macrosynthetic fibre for Rock Classes CS1, CS2 and CS3; 5 kg macrosynthetic fibres for CS4, CS5 and CS6.

15.9.3 Project key points

- The macrosynthetic fibres were not in the original design of the project, which assumed was welded mesh in the Technical Specifications. A significant improvement was the replacement of the welded mesh (150 x 150 x 7.5 mm) with macrosynthetic fibres in the lining for the support classes CS4, CS5 and CS6. This speeded up the cycle times and minimized the execution time, without affecting the structural capacity of the lining as a whole. Calculations were made to check the resistance to bending, shear and punching of the fibre reinforced solution. These calculations verified the suitability of macrosynthetic fibres and determined the lining thickness and the dosage of fibres necessary for the support.

- Changes in dosage and operation of sprayed concrete were aimed at the improving the early age strength to permit faster re-entry in order to improve the cycle times while maintaining quality and safety. Through a study of the entire process, improvements have been made in the maintenance of spraying equipment, testing and training of operators. Improving the dosing and spraying of the concrete has increased advance rates for the tunnels.

- The quality control tests have been implemented as an effective part of the construction cycle, which does not slow down the progress but rather improves it. By performing the tests at the face, any faults can be corrected there and then, without having to go back in the tunnel later.



Open Pit Mine: 5 km long 3 km wide and just over 1 km deep.



Spraying concrete at the tunnel face.

15.9.4 Picture Reference

15.10 KINGSGROVE RAMPS, AUSTRALIA

15.10.1 Project Details

History & brief description :

As part of the 33 km long Westconnex M5, a major new underground motorway in Sydney, Australia, there is a shaft and adit at Kingsgrove. Besides acting as the temporary access for tunnelling, part of the adit will form part of the permanent works of the road tunnel. The tunnel is quite shallow, located in sedimentary rocks under the Wolli Creek which added additional geotechnical risks such as reduced rock cover. The tunnel runs under the existing M5 motorway.

Year : 2017-2018.

Client and Location :

Sydney, Australia.

Type of tunnel : Road tunnel.

Ground conditions : Ashfield Shale & Hawkesbury Sandstone.

Alignment length : 25 m.

Depth : less than 17 m (to axis level).

15.10.2 Design Approach Adopted

Design method : Like many road tunnels in Australia, these tunnels are designed as drained with a permanent sprayed concrete lining. In this case, because of the low cover and its permeable nature and the proximity of the Wolli Creek, a spray applied waterproofing membrane was added between the layers of concrete. A composite lining design approach was used but without relying on longterm shear transfer by the membrane. The secondary lining was designed to carry 50% of the load with an additional check for the case if only 10% of the load is transferred (i.e. the “unbonded” case).

3D numerical models featured prominently in the design so that the effects of the adjacent structures, surface loads and junction geometry could be considered explicitly, as well as examining the impact of different properties at the lining-membrane interface.

Additional tensile reinforcement was added horizontally above the opening between the adit and the main tunnel.

The adit was excavated from the shaft. The construction sequence for the adit was Top Heading, and Bench with a split Top Heading used for the start of the main tunnel.

Sprayed concrete strength :

Primary & secondary lining 40 MPa, flexural tensile strength, $f_{R4k} = 3.0$ MPa.

Lining thickness :

Primary lining = 300-350 mm with 35-40 kg/m³ of steel fibres; Secondary lining = 200-300 mm with 40 kg/m³ of steel fibres & 1 kg poly-propylene fibres for fire resistance.

Inner and outer diameter :

10 m span for the temporary adit with an effective span of 19 m at the junction with the 16.5 m span motorway tunnel.

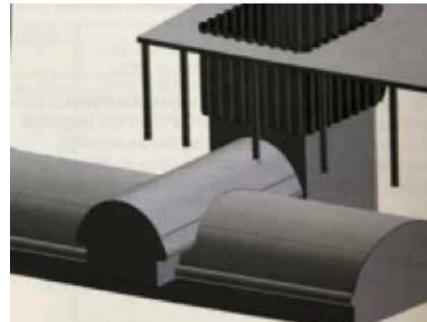
15.10.3 Project key points

- Shallow tunnel with alluvial soil cover and possible water paths through the weathered rock;
- 26 m long $\Phi 139$ mm canopy tubes installed from the shaft to improve overhead stability;
- > 2.5 MPa for personnel re-entry;
- Tight limits on settlement were met;
- Polypropylene fibres reduced the potential average spalling to < 25 mm under a 2 hour HC fire curve.

Typical secondary lining mix design :

COMPONENT	QUANTITY
Cementitious binder	430 kg/m ³
Aggregate	540 kg/m ³
Sand	1080 kg/m ³
Fly ash	25%
Microsilica	7%
Accelerator	6 – 8%
Plasticiser	5 l/m ³
Water	190 l/m ³

15.10.4 Picture Reference



General arrangement of the temporary adit, shaft and main tunnel.



A specimen from fire testing (2 hour HC curve) with 1 kg/m³ polypropylene fibre.

The following section will focus on the principles of proper application when applying sprayed concrete, which is valid for both PSCL and normal SCL. Guidelines for sprayed concrete execution are provided by many organizations, e.g. EN 14487-2 (2006), Austrian Sprayed Concrete Guideline (2013), and ACI 506R-16. The latter focuses on hand spraying but the main principles and many of the guidelines are also relevant for mechanized application.

The focus of this section will be on mechanized spraying and on the main aspects needed for proper application. Additionally, some key guidelines are highlighted below.

16.1 PREREQUISITES

There are some aspects that need to be in place and done correctly before any sprayed concrete application can be performed. Some key prerequisites are:

- Area free from people who are not authorized or needed. See 11.2 on exclusion zones.
- Area well-lit and with sufficient ventilation to control dust and other emissions.
- Correct Personal Protective Equipment (PPE) utilized. In regard to dust or inhalation of hazardous materials, PPE should only be used where control of these hazards by ventilation alone has been shown not to be reasonably practicable. There are different requirements in different locations.
- Appropriate First Aid equipment and fresh water in the vicinity of the spraying operation.
- Proposed mix has been checked and tested.
- Pre-construction tests to assess standard accelerator dosage and to check the robustness of the system are advisable.
- Checks on the concrete: delivery notes (also water-cement ratio below 0.5), workability (roughly about 600mm on a flow table (EN 12350-5:2009)) and temperature (between 15 and 22°C as guidance) on arrival, visual assessment (no bleeding and separation).

- Upon spraying, accelerator dosage to be adjusted to meet the required setting and strength development (J2 strength development (EN 14487) is sufficient for most applications).
- Spraying in “boxes”, onto wall or floor to confirm early strength values by readings.
- When spraying onto frozen ground, which is a very rare case, special measures must be taken such as including a first, sacrificial layer of concrete.
- Ensure that safe, well-maintained and proper equipment is used. It is crucial that the equipment is cleaned and maintained regularly to minimise slowdowns, breakdowns and blockages
- Starting the spraying operation must be done correctly, e.g. by following the EFNARC guidelines
- Operator (nozzleman) and crew should be aware of the required properties of the sprayed concrete lining, required thickness, profile, any safety-critical elements that need extra attention
- Operator should be properly trained and certified to spray.
- Check that all work previous to spraying is done, preferably document this and, if needed, ensure it has been approved by the client.

16.2 SURFACE PREPARATION

The quality of the placement depends also on the preparation of the surface or substrate before and after application. Simplified general guidelines for different surfaces are:

- Rock and sprayed concrete → needs washing or cleaning.
- Soft ground loose rock → very likely that less or no cleaning is needed or advisable.
- Ground sensitive to water → no cleaning.
- (Need for pre-wetting should be determined depending on conditions).

More detailed guidelines on the surface or substrate preparation, where needed:

- Remove loose rock by water jetting or mechanical scaling.
- Wash receiving surface; ensure a damp

surface without any dust, loose rock or other contaminants that may have a negative effect on the bond between the surface and the sprayed concrete layer.

- Re-clean the surface if this was done days or weeks earlier. It should be clean before spraying the concrete. High-pressure water jetting is preferred over washing only for concrete substrates. The surface should be in a saturated surface-dry condition before spraying. Sandy substrates require specific actions.
- Provide moisture to the dry substrate (especially previously placed sprayed concrete), so that it doesn't soak water out of freshly placed sprayed concrete, leading to lower bond values.
- Start surface cleaning in the top upper section and move downwards in a structured way utilizing the boom movement to be efficient.
- Ensure there are no water leakages on the surface, e.g. leaking faults or bolts/bolt holes. If in the open air, such as a shaft or an open pit, cover from possible rain.
- If the ambient temperature is expected to be below +5 ° C during the spraying or the curing period, precautions should be taken to protect the concrete from damage due to freezing.
- If the ambient temperature is predicted to be high during the spraying or during the curing period, precautions shall be taken to protect the concrete from damage.

16.3 OPERATOR POSITION AND SAFETY

The operator position is very important because it impacts on the operators' health and safety. It also affects the quality of the application because the operator needs to have a good view of the spraying.

Using the proper equipment, mix-design and the working environment during sprayed concrete application reduces the occupational health and safety risks for the operator and crew. It is good practice to engage the machine supplier in safety discussions and in safety-specific training. Best practice is summarized below:

- The operators should be in a safe, stable position and able to move around to have clear visibility.
- The operator must NOT be positioned under unsupported rock or freshly sprayed concrete. In decent quality hard rock conditions, the operator might often be under (safe) unsupported rock but, of course, never under unscaled rock. This is often the case when safety shotcrete is only applied where it's needed, and other areas are left waiting for PSCL. One example of a safe position is next to the machine with some options to move around as necessary. Spraying from a fixed position, such as the cabin, may reduce visibility and lower the quality of the application.
- Avoid sprayed concrete with alkaline accelerators as they may have a negative impact on durability and final strength as well as negative effects to the environment. Additionally, they are very harmful in terms of occupational health and safety due to the high pH value.
- During sprayed concrete placing, the dust, particulates and other emissions should be controlled so that the use of respiratory protective equipment is not required outside the immediate area of spraying, and ideally not required at all. This should be confirmed by regular monitoring. Steps should also be taken to ensure that there is no build-up of dust containing respirable crystalline silica (RCS) on horizontal surfaces.

16.4 PROPER APPLICATION OF SPRAYED CONCRETE

Sprayed concrete must be applied by qualified personnel to ensure the desired and designed quality is achieved. Proper application results in a durable and strong lining with the minimum amount of dust and rebound, and maximum bonding and compaction. These factors are greatly influenced by the nozzle angle and distance to the receiving substrate.

- Nozzle angle should be perpendicular to the receiving surface, i.e. as close to 90 degrees as possible. The wrong

angle significantly increases rebound and creates undulating surfaces, resulting in reduced compaction, hence reduced strength and significantly increased rebound. No pushing or sliding of sprayed concrete should occur.

- Distance between the nozzle and the surface is determined by site conditions and what is required for good compaction, full encasement of the reinforcement and minimum rebound. For rock support normally a distance of 1-2 meters from the receiving surface is recommended.
- Spraying should be done to minimise the risk of loosened blocks falling and concrete sagging or falling. Any loose block hanging in mesh reinforcement must be removed.
- First, in weaker ground fill all overbreak and zones of weakness, such as fissures, faults and gravel zones. Filling overbreak in hard-rock is not always necessary, where the spraying isn't done to any specific theoretical profile.
- Second, perform structured spraying, start from the bottom section moving upwards to the crown. Starting from the bottom ensures that no rebound is trapped there. Work backwards and forwards before moving up the wall.
- Avoiding capturing rebound is especially essential in soft ground tunnelling, since the overall stability relies on the integrity of the lining.
- Spray the walls first and then the crown. Start the application at the walls and moving to the crown from both sides to create an arch.
- Move the nozzle in a controlled manner, rotating it continuously in a series of circular or oval movements or use the automated nutation function if provided.
- The specified sprayed concrete thickness may require the application of two or more layers instead of spraying the entire thickness in one pass. This helps to avoid sagging or sloughing. Apply additional layers only when the preceding layer can support it. This means allowing the previous layer to harden slightly or stiffen to prevent separation and to minimise the

risk of falls of concrete.

- When spraying reinforcement such as mesh, rebars or lattice girders, it is important to spray around the reinforcement to avoid air pockets and voids. It is also important that the reinforcement is firmly fixed to limit vibrations during concrete placement. Experienced operators mostly fix lattice girders first by spraying along them (after they have sprayed and covered the bottom part of the section). Spraying through lapped mesh may also produce spray shadows, voids and low concrete compaction. If unavoidable, it must be performed with special care.
- For hard rock, fibre-reinforced sprayed concrete is usually a lot faster and cheaper than using mesh because it follows the contour of the excavation which reduces the material volume as well as removing fixing activities.
- Any running water, which normally only occurs when spraying the primary layer, should be dealt with prior to sprayed concrete application, for instance using half pipes to direct it into the drainage.

17.1 DETAILS OF CERTIFICATION SCHEMES

Currently there are several different certification schemes operating in the world which have been adopted by many different projects. Examples are listed below in Table 10 with the ones in bold text further explained.

17.2 EFNARC C2

This certification scheme focuses on assessing, training and developing both novice and experienced operators. The certification can be obtained after passing a five-day training course combining several different modules (see Table 11). Operators also need to prove that they have at least 8 weeks of spraying experience before obtaining the certificate. However, no prior experience is required to attend the course. Assessments of experienced operators, with a minimum three years of experience, are also done by EFNARC as a part of their 'EFNARC Nozzleman Certificate', launched in 2009.

17.3 ASQUAPRO

This scheme conducts training of both novice and experienced operators in France. Training is delegated to either a registered training company or an entity responsible for training within a company in the form of internships. These internships are held in companies or training centres. There are three approved centres in France so far. The duration of the training is 4.5 days for project operators and comprises:

- Theoretical instruction, in class with assessment by multiple choice test
 - Live spraying and tests
 - Visual and measured assessment of spraying tests
 - Evaluation by an 'examiner', who cannot be the trainer
- Source; <http://www.asquapro.com/en/en-certification.html>

ORGANIZATION	CERTIFICATE	SPRAYING TYPE	EXPERIENCE	SCHEME	LOCATION
EFNARC	EFNARC C2 ENC C2 V1.020190502	Robotic Spraying	Novice & Experienced operators	Training & Assessment	Global
EFNARC	EFNARC Nozzleman Certification	Robotic Spraying	Experienced operators (> 3 years)	Assessment	Global
ASQUAPRO	ASQUAPRO Certification	Robotic and hand Spraying	Novice & Experienced operators	Training & Assessment	France
Swedish Transport Administration	Sprutning med sprutbetong inom Trafikverket¹	Robotic Spraying	Novice & Experienced operators	Training & Assessment	Sweden
Australian Government	R11UND310D	Robotic Spraying	Novice & Experienced operators	Training & Assessment	Australia
American Concrete Institute (ACI)	ACI CP-60	Hand Spraying	Experienced operators (> 500 hours)	Training & Assessment	North America

¹ Translation: Spraying concrete within Trafikverket's tunnels

Table 10 : Examples of Certifications Schemes

Module	EFNARC C2 COURSE				
	1	2	3	4	5
Description	Theory session	Theory exam	Virtual training and assessment	Practical session	Work experience
Duration	Approx. 1 day	Approx. 1 hour	Approx. 3 days	Approx. 1 day	
Day	Day 1	Day 5	Day 2-4	Day 5	
	5 days				> 40 days

Table 11 : Showing the different modules included in EFNARC C2. Source: EFNARC C2 training and certification plan ENC C2 V1.0 2019-05-02

17.4 SWEDISH NATIONAL CERTIFICATION “SPRUTNING MED SPRUTBETONG INOM TRAFIKVERKET”

‘Spraying concrete within Trafikverket tunnels’ is a sprayed concrete operator certification and training course required for major tunnelling projects in Sweden by the Swedish Transport Administration, Trafikverket. This started as a project-specific requirement for the E4 Stockholm Bypass project in Sweden. Now, it has been adopted by various projects where The Swedish Transport Administration is the tunnel client. There are also other tunnel clients, such as Public Transport Stockholm, that have required this certification in their projects and hence it could be considered a national standard in Sweden.

The training course lasts for eight-to-ten days. The first four-to-five days include a classroom theory session and a sprayed concrete test methods session. During the last three-to-five days, participants go through a practical session with simulator training and assessments in virtual reality. The training course ends with a theory test, conducted and approved by The Swedish Transport Administration. After the training, the operator needs to hand in a document proving at least two months of concrete spraying experience to obtain the certification.

Source : https://www.trafikverket.se/contentassets/c34f5b28f9fd49e494931df2364c655c/utbildningsplan_fs_bergforstarknig_sprutbetong_certifieringskurs_v08.pdf

18.1 INTRODUCTION

Toughness is generally the main criterion for FRSC as ground support. However, for the FRSC to have the highest strength and toughness, there must be an optimal design that combines concrete strength, fibre anchoring and placement method for the specific design case.

Consequently, the choice of fibre type and content must correspond to the ground conditions of a specific area and the expected concrete mix design.

18.2 OVERVIEW OF MAIN TEST METHODS

There are several test methods relating to Fibre Reinforced Concrete from different regions. The main test methods are presented below. While tests on unnotched beams are commonly used, these are not recommended because of the high scatter in results. Tests on notched beams (e.g. according to EN 14651) are recommended.

18.2.1 Testing with continuous support

The EN 14488-5 test method is a European standard meant for the determination of the energy absorption capacity of FRSC (EN 14488-5, 2006). In this procedure, a square FRSC slab specimen is loaded in its centre with a square steel head and continuously supported by a rigid steel frame on its entire perimeter.

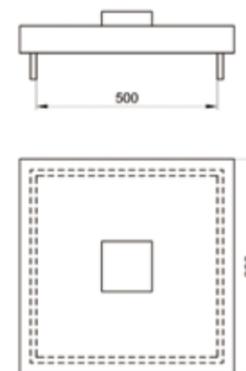


Figure 8 : EN 14488-5 test plate dimensions

This standard gives a load-deflection curve and an energy absorption-deflection curve that represent the behaviour of FRSC under a combination of flexural load and punching shear load.

The energy absorption at a 25 mm deflection can be used to classify FRSC in different energy absorption classes such as E700 (700 J) or E1000 (1000 J) for example. Ultimately, this value can be used as a parameter in the empirical ground support design method Q-system [38] and for quality control of FRSC.

ASQUAPRO, the French Association for Quality of the Projection of Concretes, offers additional recommendations on the EN 14488-5 test. First, it recommends that the value of absorbed energy exceeds 500 J. Secondly, it gives recommendations on the behaviour of the FRSC to verify the ductility of the composite material, using criteria that describe the shape of each curve obtained and are meant to reject brittle composites behaviour. These criteria state that the maximum load in the elastic zone (F_{max-el}) must be reached at a deflection of less than 2 mm and that the minimum load after cracking and up to a 5 mm deflection must be of at least 70% of this F_{max-el} . This test method probably comes closest to the actual loading conditions in a ground support scheme with bolts. It is a statically indeterminate setup which allows for load redistribution and it creates both flexural and punching shear stresses leading to more realistic, albeit complex, failure modes.

NB: The Norwegian standard test (Norwegian Concrete Association, 2011, 2021) is very similar to the EN 14488-5; the shape of the panel is essentially the same, a rigid frame supports a circular panel on its perimeter as a circular piston applies the load at the centre of the panel. A load-deflection curve and an energy absorption-deflection curve are produced. The test specimen is a circular slab of 600 mm in diameter and 100 mm in thickness on a 500 mm diametral span.

18.2.2 Round Panel test

The ASTM C1550 Standard Test Method for Flexural Toughness of Fibre Reinforced Concrete (Using Centrally Loaded Round Panel) is a four-point bending test.

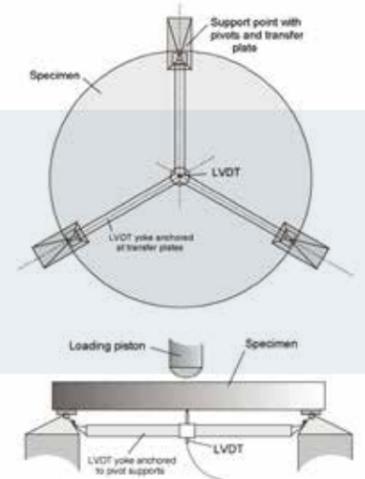


Figure 9 : RDP test set-up

This test method does not allow for load redistribution between different cracks as it is statically determinate. Hence it tends to show much less scatter in results than statically indeterminate tests, on both, beams or panels. (Bernard & Thomas 2020).

The result from this standard is a load-deflection curve that represents the post cracking flexural behaviour of FRSC. From the results, the uncorrected and corrected peak load and energy absorptions are calculated. The values of energy absorption are typically reported at central deflections of 5, 10, 20 and 40 mm.

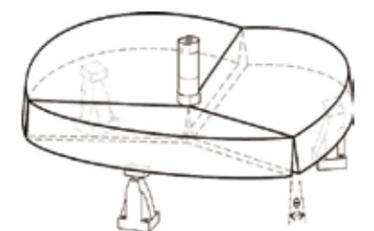


Figure 10 : Determined failure in RDP test

For ASTM C1550, the energy absorbed up to 5 mm central deflection is applicable to situations in which the material is required to hold cracks tightly closed at low levels of deformation. Examples include final linings in underground civil structures such as railway tunnels that may be required to remain water-tight. The energy absorbed up to 40 mm is more applicable to situations in that the material is expected to suffer severe deformation in situ (for example, shotcrete linings in mine tunnels and temporary linings in swelling ground). Energy absorption up to intermediate values of central deflection can be specified in situations requiring 20 mm performance at intermediate levels of deformation.

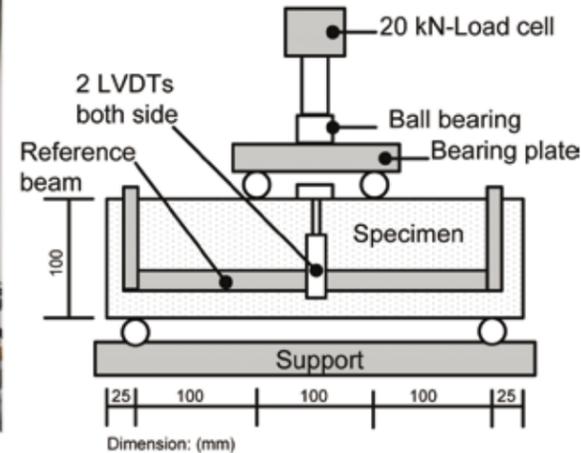


Figure 11: Four point bending test set-up

18.2.3 Four point bending test on beams

Note that this is an unnotched beam test and therefore not generally recommended, as explained above.

The ASTM C1609/C1609M test method is an ASTM standard intended for the evaluation of the post-cracking flexural performance of FRSC. It can be used to test shotcrete samples, providing that the specimens from shotcrete material test panels are prepared in accordance with standard practice. It is designed to test concrete with any type of fibres.

This test method is popular with structural designers who use the ACI 318M code because the equations in this document are based on results from this test method. In theory, it is also possible to calculate the stress-crack width behaviour of FRSC with this test method. However, since the crack is not necessarily in the middle of the beam, it is not as simple to derive this relationship as it is with EN 14651.

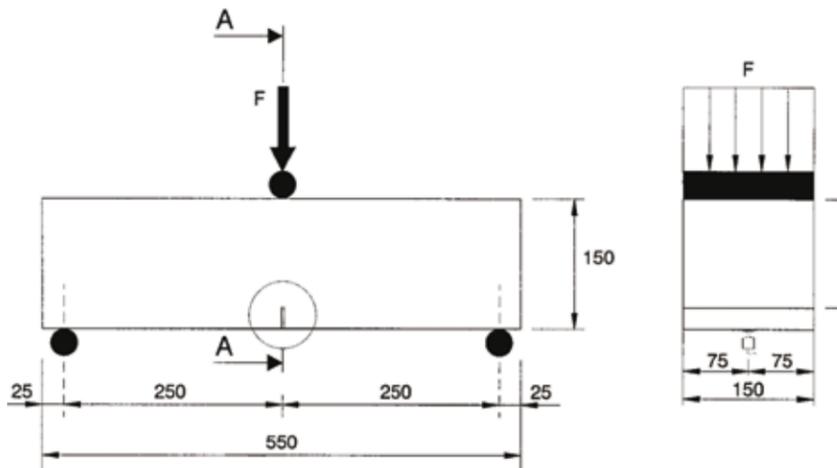


Figure 12: Three-point bending test set-up with notch

18.2.4 Three-point bending test on a beam with a notch

The EN 14651 test method is a European standard designed to measure the post-cracking flexural tensile strength of fibre-reinforced concrete. It can be used to evaluate FRSC samples. It is initially intended

for testing concrete with metallic fibres but can also be used with synthetic fibres.

The advantage of the notch in the beam is that crack growth is more controlled which generally leads to less scatter in the results. This standard test method is often preferred in many countries as it provides information

that can be directly used for structural design with fib Model Code 2010.

This test is the most suitable to get relevant residual flexural tensile strengths for design calculations.

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