Sprayed Concrete: A Modern, Holistic Approach

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1 Abstract

The paper gives an overview of the improvements in sprayed concrete technology that have occurred rapidly over the last 10 years, allowing the industry to consider sprayed concrete as a "permanent" structural support. Consequently, its implementation as a support system has increased dramatically worldwide. The developments have been focused on attaining high quality, homogeneous, environmentally safe sprayed concrete via the adoption of the wet-mix process using robotic spraying techniques coupled with advances in sprayed concrete mix design, particularly operator- and structure-friendly liquid accelerators.

As highlighted in the paper, emphasis within the industry now needs to be given to a more holistic approach to creating durable sprayed concrete structures using the modern application systems described. With a construction method whose success is fully dependent on human influence, the paper provides an overview of critical elements such as contractor and designer experience and site control systems. Furthermore, the need for modern, up-to-date specifications to reflect current technology are suggested, coupled with the industry-wide need for relevant nozzleman training and recognised certification schemes.

2 Introduction

The durability of a tunnel lining should be such that the lining remains safe and serviceable for the designed life, without the need for a high degree of maintenance expenditure. To attain durability, the designer needs to assess the exposure environment of the structure dur-

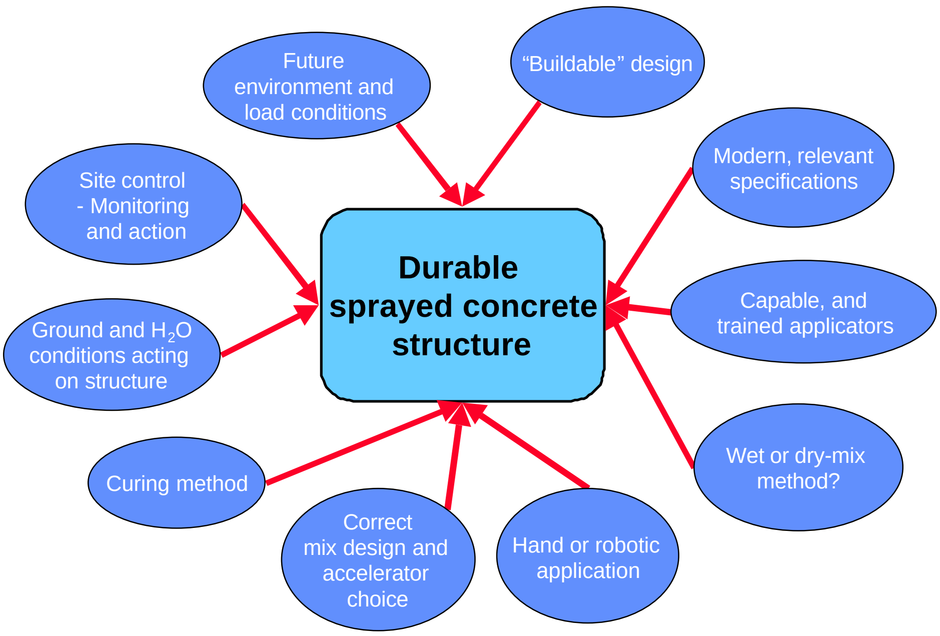


Figure 1: Factors that significantly determine the durability of a sprayed concrete structure

ing both construction and operation, as structural degradation normally occurs with unforeseen environmental changes.

With this in mind, the term durability may be related to structures that are designed to resist loads during a construction period before a secondary lining is placed. However, more often, with the use of sprayed concrete for permanent single shell linings, the durability of the concrete should consider a design life of 100 years or more. It is this latter case that is the focus of the presentation and paper.

As can be seen from Figure 1, the durability of a sprayed concrete structure is established via a total of many possible parameters. In sprayed concrete construction, not only correct concrete mix design and cover to reinforcement as with traditional cast concrete is sufficient. The main reason behind this is that the material is spray applied, and consequently the quality is significantly reliant on human skills and spray equipment performance. The main durability issues listed in Figure 1 are briefly discussed in this paper.

3 Buildable Designs

With respect to existing concrete tunnel structures, the major durability problems are not directly related to the concrete itself, but more often to the corrosion of steel reinforcement elements that have been insufficiently protected against water ingress or humidity. Tunnels constructed with permanent sprayed concrete create other durability concerns, particularly in terms of providing the required material properties such as compaction, and with the unknown stability concerns associated with the necessary amount of admixtures used for modern wet-mix sprayed concrete application methods.

As summarised in Figure 2, to address the durability requirements, a holistic approach to the design and construction of durable sprayed concrete tunnel linings is required. In essence, the sprayed concrete lining method is heavily reliant on human competence during construction, and therefore the design should reflect this by considering the “buildability” of tunnels using sprayed concrete.

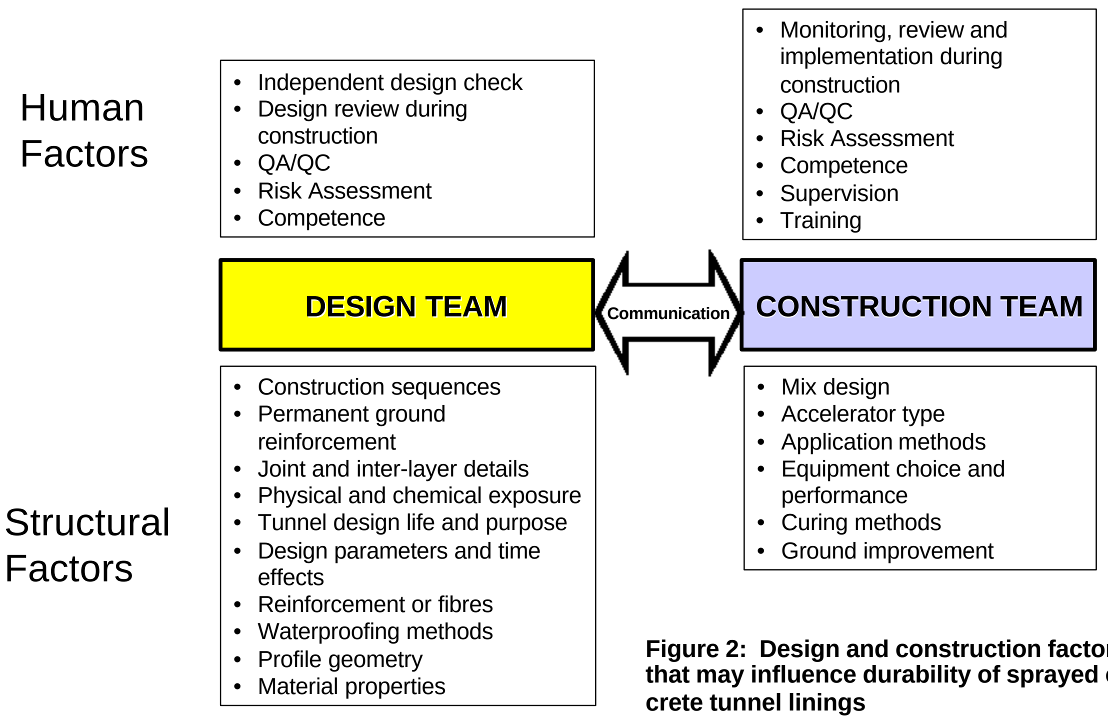
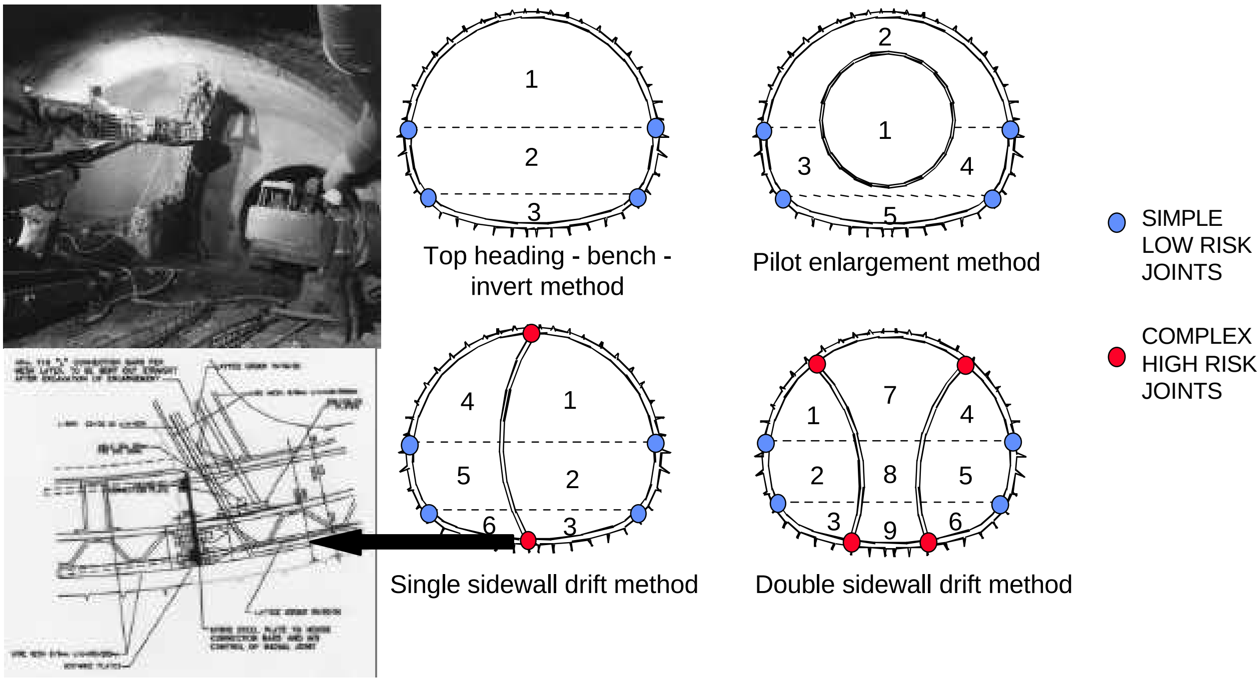


Figure 2: Design and construction factors that may influence durability of sprayed concrete tunnel linings

Designing “buildability” ensures that safety and durability critical elements are either designed out, or simplified for ease of construction on the job site. An example of this could be the construction of large diameter tunnel with sprayed concrete in soft ground. As indicated in Figure 3, options available to the tunnel designer may be the construction adopting the sidewall drift method, or perhaps instead using the pilot enlargement method. The latter option is a simpler form of construction, and does not present poor compaction and subsequent potential corrosion problems at complex construction joints as seen with the sidewall drift method.



Furthermore, design teams should be aware of the limitations of construction processes, and be familiar with the likely material performance, and should have a strong site presence to ensure that the critical safety and durability features are constructed as per the design.

4 Specifications and Guidance

Unfortunately, too often in the sprayed concrete industry, specifications and guidance documents tend to be “cut and pasted” into new contracts year after year, without much in depth research as to the current advanced state of the sprayed concrete business. The recent increase in wet-mix sprayed concrete has provided an opportunity to re-examine the “old” specifications, and now new documents are emerging which reflect the current state-of-the-art in sprayed concrete technology.

These modern sprayed concrete specifications now specify permanent, durable sprayed concrete for the first time as a construction material. They address the issues of achieving a quality controlled modern mix design, providing guidance on promoting and testing for durability and effective execution of the spraying processes. As an example, the new European Specification for Sprayed Concrete (1996) produced by EFNARC, provides comprehensive systems to attain permanent sprayed concrete. This specification has been the basis for new project specific specifications world-wide, and for the new European Norm Sprayed Concrete Specification.

Furthermore, the EFNARC Sprayed Concrete Specification is the first document to address issues such as national nozzleman training and accreditation. The Specification also sets out systems for contractors and specifiers/designers to consider, prior to construction, the sprayed concrete structures they are to build, so as to adapt the sprayed concrete system and mix design accordingly.

5 Construction competence

The construction team should be made aware of the design elements that are key factors in determining the safety and durability of the tunnel structure. To ensure the quality of the concrete lining is achieved, quality review systems should be adequate to control the production. It is of paramount importance that the communication link between design and construction teams should be maintained from pre-design stage to project completion so that the above processes are promoted.

Nozzlemen should have previous experience in the application of sprayed concrete, and have knowledge of the sprayed concrete process to be adopted on the specific project. It is recommended that an operator be able to demonstrate his experience either as a holder of a certificate from previous work, or required to demonstrate his competence in a non-works location.

Prevailing regulations place added requirements on the people doing the spraying work to have technical knowledge of concrete, particularly with sprayed concrete. Present requirements have led to a better training of the personnel involved. The result of this is an improved quality of work. The number of special contractors who are working with sprayed concrete has increased over the last few years, which has globally raised the quality of application.

To address the international issue of sprayed concrete training, an innovative service provided by the International Centre for Geotechnics and Underground Construction (CUC), based in Switzerland, are providing courses in modern sprayed concrete technology to address the shortcomings in the industry. Specific courses are available for designers and contractors, with specialist international nozzleman training for robotic spraying set to start in 2002 for example.

6 Sprayed Concrete Mix Design

The main factor that determines the durability of a concrete structure is achieving a low permeability which reduces the ingress of potentially deleterious substances, thereby inhibiting chemical reactions such as those involving the cement and thereby preventing chemical changes. Low permeability is achieved in sprayed concrete applications by the following means:

- A well graded material suitable for the sprayed concrete application system in terms of pumpability, workability, rebound reduction and good compaction (such as the EFNARC

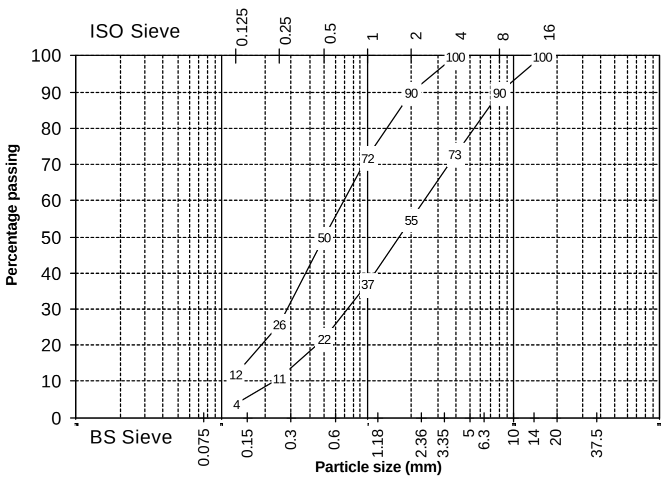


Figure 4: Proposed aggregate grading envelope for sprayed concrete (EFNARC 1996)

grading envelope given in Figure 4). All aggregates should be checked for alkali-silica reaction.

- Adequate cementitious content, typically 400 to 500kg. The cement content should not be less than 350kg.
- Low, pre-defined water/cement ratio less than 0.45, achieved using water reducing agents / superplasticisers. Modern superplasticisers, referred to as "hyperplasticisers" can provide w/c ratios between 0.35 and 0.4, whilst maintaining a slump of 20cm.
- Use of pozzolanic materials such as silica fume and PFA. Silica fume has a definite filler effect in that it is believed to distribute the hydration products in a more homogeneous fashion in the available space. This leads to a concrete with reduced permeability, increased sulphate resistance and improved freeze-thaw durability.
- Control of micro-cracking to 0.2mm by fibre reinforcement instead of mesh, thereby allowing autogenous healing.
- Controlled, low dosages of alkali-free accelerators for reduced reduction in final strength compared to base mix, significantly reduced leachates, reduced rebound and dust, and most importantly, to provide safe working conditions.
- Hydration control admixtures to prevent premature hydration of the mix before it is applied to the substrate. Pre-hydration may cause significant deleterious effects to the hardened physical properties of the sprayed concrete, such as low strengths and densities, and increased permeability.

A range of permeability tests for site testing are described in the Concrete Society (UK) Technical Report No.31: Permeability testing of site concrete (1988). Included are three concrete classes having high, average and low permeability based on typical results from the test techniques. The permeability tests and ranges for sprayed concrete are identified in Figure 5, and the test result ranges for samples from UK permanent sprayed concrete tunnels are also illustrated, clearly demonstrating sprayed concrete as a durable lining material as they are generally of "Low permeability" concrete class (Dimmock 1998).

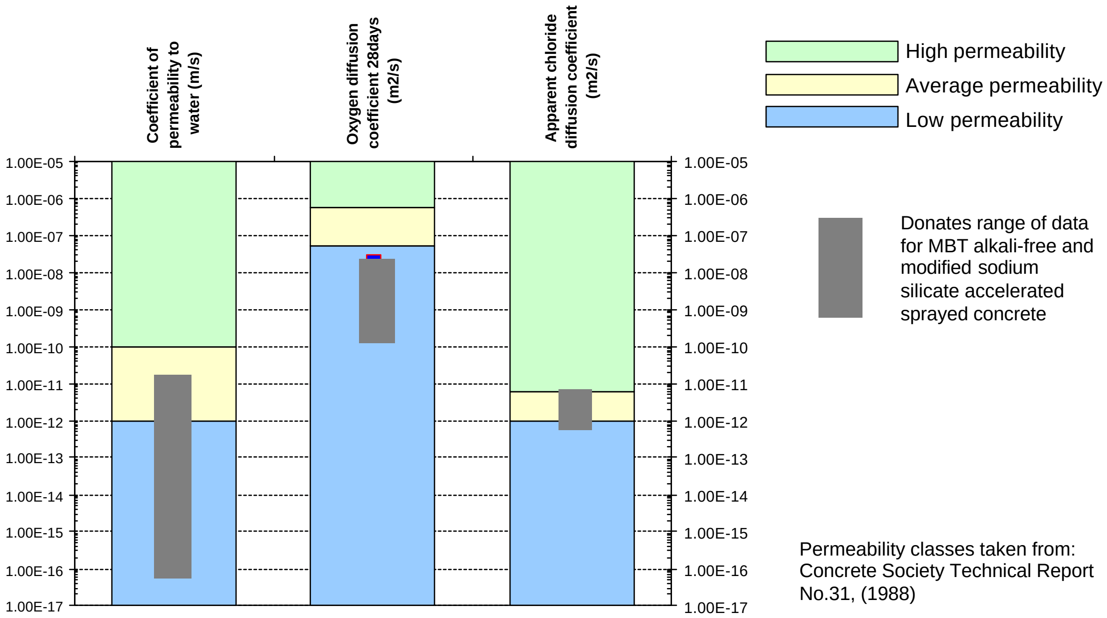


Figure 5: Permeability test and results for sprayed concrete using MBT's alkali-free and modified sodium silicate accelerators

7 New “Alkali-free” accelerating admixtures

Of late, safety and ecological concerns have become dominant in the sprayed concrete accelerator market, and applicators have started to be reluctant to apply aggressive products. In addition, requirements for strength and durability of concrete structures are increasing. Strength loss or leaching effects suspected to be caused by strong alkaline accelerators (aluminates) has forced our industry to provide answers and to develop products with better performances.

Due to their complex chemistry, alkali-free accelerators are legitimately much more expensive than traditional accelerators. However, accelerator prices have very little influence on the total cost of in-place sprayed concrete. Of much larger consequence are the time and rebound savings achieved, the enhancement of the quality, durability and the safe working environment.

The increasing demand for accelerators for sprayed concrete termed *alkali-free* always contains one or more of the following issues:

- Reduction of risk of alkali-aggregate reaction, by removing the alkali content arising from the use of the common caustic aluminate based accelerators.
- Improvement of working safety by reduced aggressiveness of the accelerator in order to avoid skin burns, loss of eyesight and respiratory health problems. The typical pH of alkali-free accelerators is between 2.5 and 4 (skin is pH5.5).
- Environmental protection by reducing the amount of aggressive leachates to the ground water, from both the in-situ sprayed concrete and rebound material deposited as landfill.
- Reduced difference between the base mix and sprayed concrete final strength compared to older style aluminate and waterglass accelerators that typically varied between 15 and 50% dosage.

The focus within different markets, regarding the above points, is variable. Where most sprayed concrete is used for primary lining (in design considered temporary and not load bearing), points 2 and 3 are the most important. When sprayed concrete is used for permanent structures, items 1 and 4 become equally important.

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

In terms of sulphate resistance, a number of tests have been carried out by SINTEF, Norway and the results are summarised in Table 1, with “High” denoting excellent sulphate resistance. A number of comments can be made regarding these results:

- Alkali-free accelerators can be used to produce sulphate resisting sprayed concrete up to dosages of 10%.
- Alkali-free accelerators perform better than modified sodium silicate accelerators with OPC cements.
- The use of 6% microsilica provides comparable sulphate resistance with OPC as with sulphate resisting cement (SR). This is important as it is preferential to use OPC rather than SR cement in sprayed concrete due to the faster setting and early strength development.
- The lower the water-cement ratio, the higher the sulphate resisting performance. It is recommended to have a w/c ratio below 0.45, and preferably with the aid of new hyperplasticisers, attain a w/c ratio of less than 0.4.

Table1: Sulphate resistance of sprayed concrete (SINTEF, 1999)

Cement Type	OPC	OPC	OPC	OPC	SR
Aggregates: alkali-silica reactivity	reactive	reactive	non reactive	non reactive	slightly reactive
Microsilica	0%	6%	0%	6%	0% and 6%
w/c ratio	0.45	0.47	0.52	0.48	0.45 to 0.48
Accelerator & Dosage					
Modified sodium silicate 5%	moderate	high	none	high	high
Modified sodium silicate 10%	none	high	none	high	high
alkali-free 5%	high	high	none	high	high
alkali-free 10%	moderate	high	none	high	high

none (no resistance) :	greater than 0.1% expansion
moderate resistance :	between 0.05% and 0.1% expansion
high resistance :	less than 0.05% expansion

8 Application requirements

Quite often, the benefits of a well engineered mix design to achieve the durability requirements of the structure are negated by poor application processes. To obtain durable sprayed concrete, and to ensure the material properties satisfy the requirements of the design, the application process should conform to the following criteria to provide a high performance concrete with minimal variance in quality:

- Thoroughly mixed (including fibres), homogenous concrete should be produced at the nozzle, and should be free from pulsation effects and blockages by using wet-mix pumps.
- Measured aggregate rebound should be below 10% providing the tunnel lining with a suitably graded material. This has the critical effect of reducing delaminations, shadows behind steel reinforcement, shrinkage cracking and poor microstructure.
- Measured fibre rebound should be less than 20% so as to provide efficient crack control and structural performance thereby imparting improved durability to the tunnel lining.
- Automated accelerator dosing units that work in synchronisation with concrete output should be used to allow accurate, consistent dosage rates.
- Low dust levels to allow greater visibility for nozzlemen to perform better control of spraying.
- The aim of the system should be to reduce the risk of human influences negatively affecting the quality of the sprayed concrete. For example, robotic spraying mobiles should be used where possible, allowing superior quality sprayed concrete to be applied in a safer, more economical manner, as demonstrated in Figure 6.
- A ready supply of sprayed concrete should be available to apply as a contingency support when excavating the tunnel. Controlling the cement hydration using stabilising admixtures can facilitate this.
- In the case of loose ground and running ground water, the system should be

Figure 6: Use robotic spraying for higher quality sprayed concrete

adjustable to provide sprayed concrete with immediate setting characteristics (flash setting).
- The method of sprayed concrete application should allow effective concrete curing that will not adversely influence the bond strength between subsequent layers, such as with the incorporation concrete improving admixture.

In view of the requirements above, it is strongly recommended that only the wet-mix sprayed concrete process be used for the construction of durable linings (Figure 7). The wet-mix process is currently the only viable method to achieve quality, particularly with respect to controlling the water cement ratio that is vital for concrete durability and long term strength. Additionally, the wet-mix process has also demonstrated significant economical benefits over the dry-mix process.

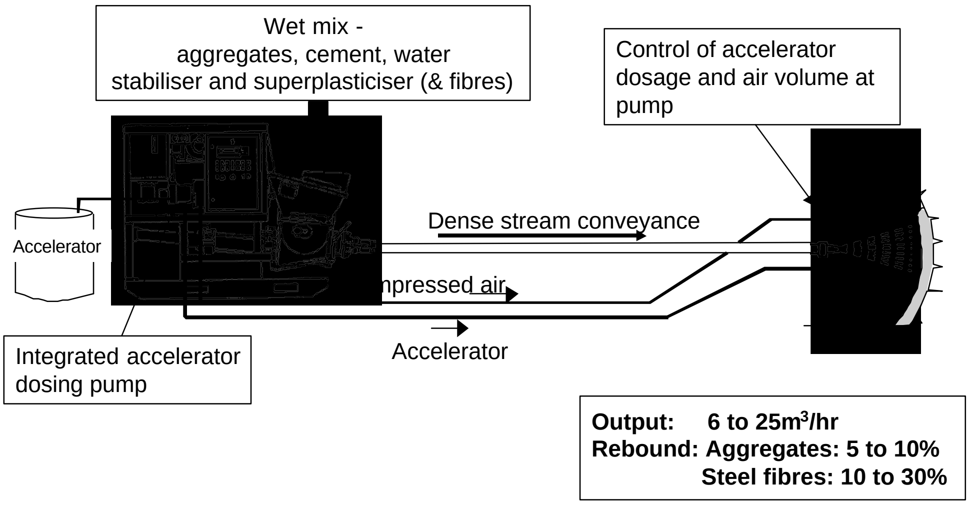


Figure 7: Wet-mix sprayed concrete process

Many of the factors that cause high rebound values, poor compaction, loss in structural performance and hence increased project costs are attributed to the performance of the nozzleman, particularly that of the hand held nozzle systems using the dry-mix process.

The advent of modern admixtures applied to wet-mix sprayed concrete has reduced these problems significantly by enabling the placed concrete to be initially plastic in nature. For some minutes after application, new sprayed concrete can be absorbed and compacted more readily than very fast, or flash setting materials. This approach reduces rebound significantly and allows steel encapsulation to be achieved more readily.

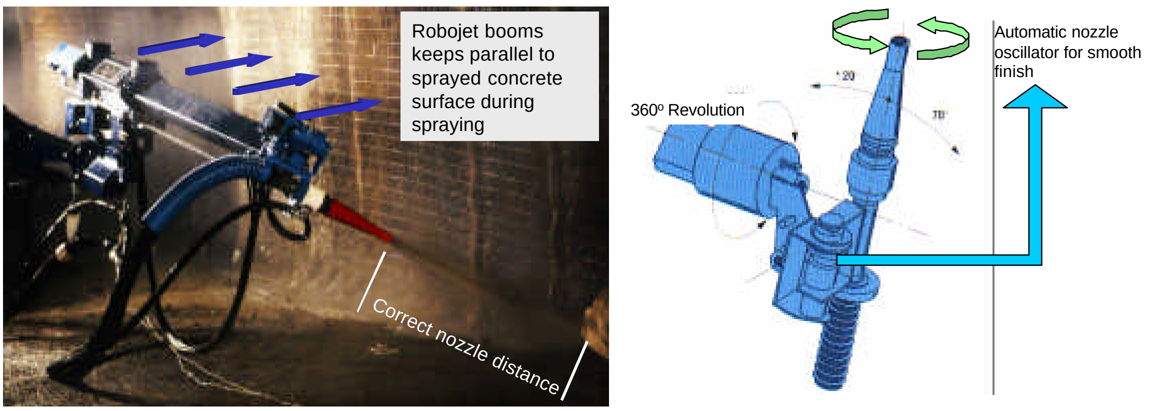


Figure 8: MEYCO Robojet spraying manipultor - correct angle and distance for reduction in rebound and enhanced quality

Problems relating to nozzle angle, nozzle distance and achieving the correct compaction with the required air volume and pressure have been facilitated by the use of robotic spraying manipulators, particularly in large diameter tunnels. As shown in Figure 8, the MEYCO Robojet spraying manipulator is controlled by a remote-control joystick by the nozzleman to allow the nozzle to be spraying at the correct distance and angle at all times. This coupled with the required air volume and pressure ensures low rebound and well-compacted sprayed concrete. Good surface finishes can be achieved by selecting the automatic oscillating movement of the nozzle mode.

9 Sprayed Concrete Curing

Curing is one of the basic and most important jobs in sprayed concrete to achieve good durability. This need is due to the relatively high cement and water content of the mix and the consequential high shrinkage and cracking potential of the applied concrete. Other reasons are the danger of rapid drying-out due to the heavy ventilation as is usual in tunnels, and the fast hydration of accelerated sprayed concrete and the application in thin layers. Therefore, sprayed concrete should always be cured properly by means of an efficient curing agent. However, the use of curing agents involves several restrictions:

- They must be solvent-free (use in confined spaces)
- They must have no negative influence on the bonding between layers
- They must be applied immediately after placing of the sprayed concrete

Most of the in-place sprayed concrete around the world has no bonding and many cracks occur, due to the fact that no curing system being implemented. With the increased use of sprayed concrete as permanent final lining material, long-term durability and performance requirements have become significant. These requirements are good bonding, high final density and compressive strengths to ensure freeze/thaw and chemical resistance, watertightness and a high degree of safety.

When curing sprayed concrete with an external curing agent, one has to be very careful with the cleaning procedure of the substrate before applying a subsequent layer. Cleaning must be done with high-pressure air and a lot of water.

Another problem with curing agents is to be able to apply them quickly enough after finishing the spraying. To secure proper curing of sprayed concrete, the curing agents must be applied within 15 to 20 minutes after spraying. Due to the use of set accelerators, the hydration of sprayed concrete takes place a very short time after spraying (5 to 15 minutes). The hydration and temperature are most active during the first minutes and hours after the application of the sprayed concrete and it is of great importance to protect the sprayed concrete at this critical stage.

Application of curing agents requires two, time consuming working operations: Application of curing agent, and the cleaning/removal of the curing agent from the sprayed concrete surface between layers, in the case of multiple layer construction.

New systems for more efficient and secure curing of wet-mix sprayed concrete have been developed, referred to as Concrete Improving admixtures. Concrete improving (internal curing) means that a special admixture is added to the concrete during batching as a normal admixture. This admixture produces an internal barrier in the concrete, which secures safer hydration than the application of conventional curing agents. The benefits resulting from this new technology are:

- The time consuming application and, in the case of various sprayed concrete layers, removal of curing agents are no longer necessary
- Curing is guaranteed from the on-set of hydration
- There is no negative influence on bonding between layers enabling structures to act monolithically without the risk of de-lamination
- Acts on the whole thickness of the concrete lining, rather than just the exposed surface

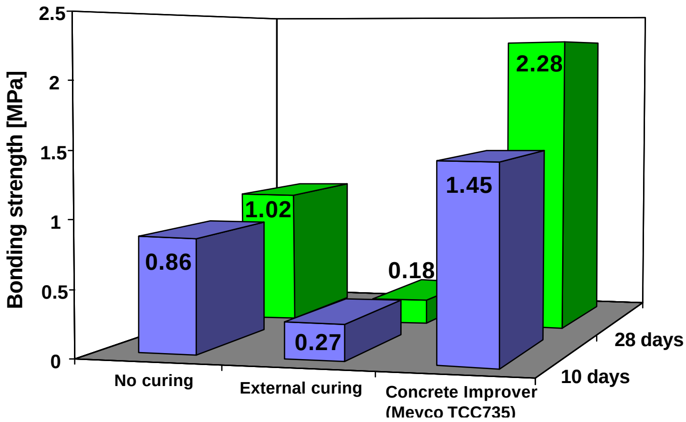


Figure 9: Positive influence of using Concrete Improvers to enable increased bond strength

Figure 9 illustrates typical bond strength results for sprayed concrete samples that have no curing, a spray applied curing membrane and finally, a sprayed concrete containing concrete improving admixture. The externally cured sprayed concrete gives the worst performance as the membrane has had a negative influence on the bond strength. The effectiveness of the Concrete Improver is also seen with age, as demonstrated by the increase between 10 and 28days.

As a consequence of this optimum curing effect, all other sprayed concrete characteristics are improved: density, final strengths, freeze-thaw and chemical resistance, watertightness, less cracking and shrinkage. In addition, it also improves pumpability and workability of sprayed concrete, even with low-grade aggregates. It also particularly improves the pumpability of steel fibre reinforced sprayed concrete mixes.

10 Steel and High Performance Polymer (HPP) fibre reinforcement

From experience, water ingress is associated with sections of the sprayed concrete lining that contain large diameter steel reinforcement, such as lattice girders, lattice girder connection bars, and excessive overlaps of steel reinforcement, as indicated in Figure 10. Therefore the emphasis should be to minimise the quantity of steel reinforcement by:

- Optimisation of the tunnel cross-sectional profile to reduce moment influences
- Increasing the thickness of the tunnel lining to maintain the line of thrust to the middle third of the concrete section
- Where structurally possible, using the more favourable option of fibre reinforcement.

Figure 10: Water ingress through sprayed concrete containing steel reinforcement

Steel fibres have been used successfully in permanent sprayed concrete tunnel projects to reduce cracking widths to 0.2mm to produce watertight, durable tunnel linings. The advantage over conventional anti-crack reinforcement is that the fibres are randomly distributed, and discontinuous throughout the entire tunnel lining structure allowing uniform reinforcement that evenly re-distributes tensile loads, producing a greater quantity of uniformly distributed microcracks of limited depth. Steel fibres also transforms the concrete from a brittle into a highly ductile material giving the lining a higher load bearing capacity, post initial cracking through the effective redistribution of load, thereby increasing the safety of the structure during construction. More recently, HPP fibres have been introduced (see Figure 11), having the added benefit of being corrosion resistant, whilst offering similar performance to steel fibres.

With all fibre mixes, care should be taken to match the fibre strength to the tensile strength of the concrete, as high strength concrete with normal tensile strength fibres may still produce a brittle material. As fibres are added during the batching process, this removes the timely operation of welded mesh installation from the construction cycle.

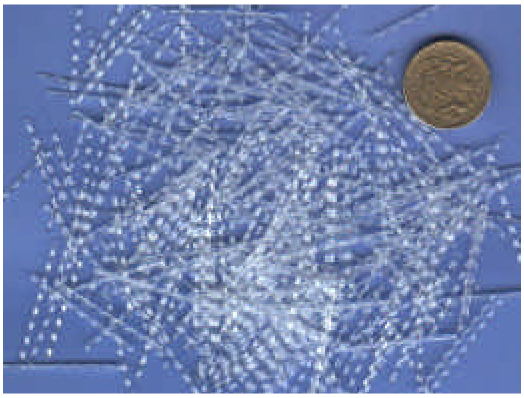


Figure 11: High Performance Polypropylene (HPP) fibres for sprayed concrete

If conventional reinforcement is required for structural purposes, then the reinforcement should be designed with the installation method in mind, and be evenly distributed. The reinforcement arrangement should be such that the nozzleman can facilitate full encapsulation of the bars, and the construction sequence can allow sequential installation of the reinforcement. Under no circumstances should sprayed concrete be applied through full reinforcement cages or excessive overlaps of mesh. Attention should also be paid to avoiding flash sets from high dosages of accelerating admixtures, as this inhibits the fresh concrete from behaving plastically and moving around reinforcement immediately after spraying.

11 Achieving watertightness – sprayable membranes

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

Traditionally, polymer sheet membranes have been used, where the system has been shown to be sensitive to the quality of heat sealed joints and tunnel geometry, particularly at junctions. Furthermore, when sheet membranes have been installed with an inner lining of sprayed concrete, the following adverse conditions can occur:

Figure 12: Using a simple screw pump, two men can apply sprayable membrane up to 50m^2 per hour

- As the sheet membranes are point fixed, sprayed inner linings may not to be in intimate contact via the membrane to the substrate. This may lead to

asymmetrical loading of the tunnel lining.
- To aid the build of sprayed concrete onto sheet membranes, a layer of welded mesh is used. Due to the sheet membrane being point fixed, the quality of sprayed concrete between the mesh and the sheet membrane is often inferior, and may lead to durability concerns.
- The bond strength between sprayed concrete inner lining and sheet membrane is inadequate and leads to potential de-bonding, particularly in the crown sections of the tunnel profile. This is a detrimental effect when constructing monolithic structures.
- As there is little bond strength at the concrete - sheet membrane interface, any ground water will migrate in an unlimited manner. Should the membrane be breached, the ground water will inevitably seep into the inside tunnel surface at any lining construction joint or crack over a considerable length of tunnel lining.

To combat these problems, MBT have developed a water based polymer sprayable membrane, Masterseal® 340F.

This sprayable membrane has excellent double-sided bond strength (0.8 to 1.3 MPa), allowing it to be used in composite structures, and thereby effectively preventing any potential ground water paths on both membrane–concrete interfaces being created. Masterseal® 340F also has an elasticity of 80 to 140% over a wide range of temperatures allowing it to bridge any cracks that may occur in the concrete structure. Being a water based dispersion with no hasardous components, it is safe to handle and apply in confined spaces. The product can be sprayed using a screw pump and requires two operatives to apply up to 50m^2/hr, particularly in the most complex of tunnel geometries, where sheet membranes have always demonstrated their limitation, as shown in Figure 12.

As presented in Figure 13, in single shell lining applications, Masterseal® 340F is applied after the first layer of permanent fibre-reinforced sprayed concrete, where the sprayed surface should be as regular as possible to allow an economical application of membrane 5 to 8mm thick (all fibres are covered also). A second layer of permanent steel fibre reinforced sprayed concrete can then be applied to the inside. As the bond strength between the Masterseal® 340F and the two layers of permanent sprayed concrete is about 1MPa, the structure can act monolithically, with the sprayable membrane resisting up to 15bar. As this appli-

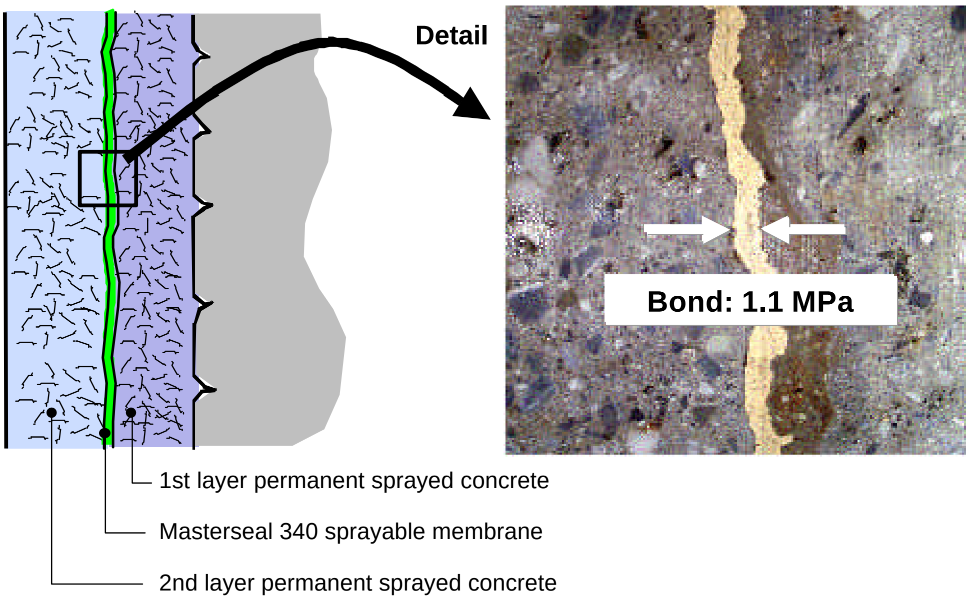


Figure 13: Composite, watertight structures using Masterseal 340F sprayable membrane

cation considers no water drainage, the 2nd layer of sprayed concrete must be designed to resist any potential hydrostatic load over the life of the structure.

12 Provision of fire protection

In recent years, the tunnelling industry has been shocked by the rapid devastation, and in some cases loss of life caused by very notable fires, such as the Channel Tunnel (Figure 14), Mont Blanc and more recently, tunnels in Austria.

Whilst systems are being developed to further secure the safety arrangements of passengers and operatives of tunnels during tunnel fires, clients are increasingly requesting that structural tunnel linings remain fire damage resistant. Master Builders Technologies, along with other companies, has addressed the issue of providing effective protection to tunnel linings to avoid extensive fire damage, and significantly reduce the risk of lining and ground collapse during the fire event.

Figure 14: Channel Tunnel fire damage

The philosophy behind MEYCO® Fix Fireshield 1350 is to provide a passive fire-protective layer to any underground structure using a rapid spray application process, as indicated in Figure 15. Furthermore, the protective layer should be as thin as possible to reduce effects on the required structural envelope. If attacked by fire, the underlying structural concrete would be protected for temperatures up to 1350ºC. Repair is simply completed by local removal of the damaged protection layer and re-sprayed with a new application.

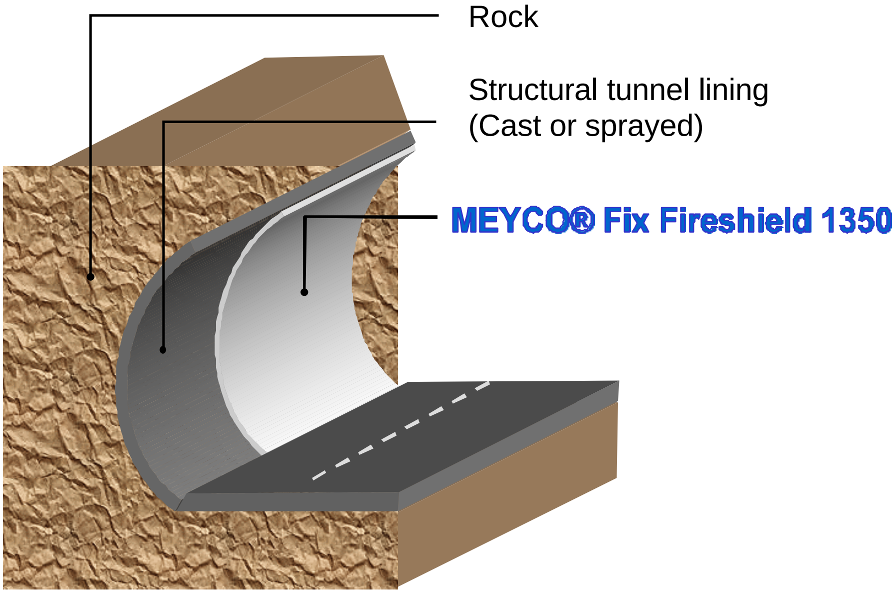


Figure 15: Sprayed application of passive fire protection layer to structural sprayed or cast concrete tunnel lining

The performance of such passive fire protection systems are currently established at the TNO Test Centre for Fire Research, Delft, Netherlands. To simulate a petrol tanker fire in a tunnel, the Dutch RWS fire curve is currently specified for testing fire protection systems for underground structures. Apart from the temperature being above 1200ºC for two hours and a maximum temperature of 1350ºC, the test also puts the system under immediate thermal shock. See Figure 16 for time-temperature curve of furnace temperature, and corresponding curve for interface temperature between fire protection and structural concrete sample.

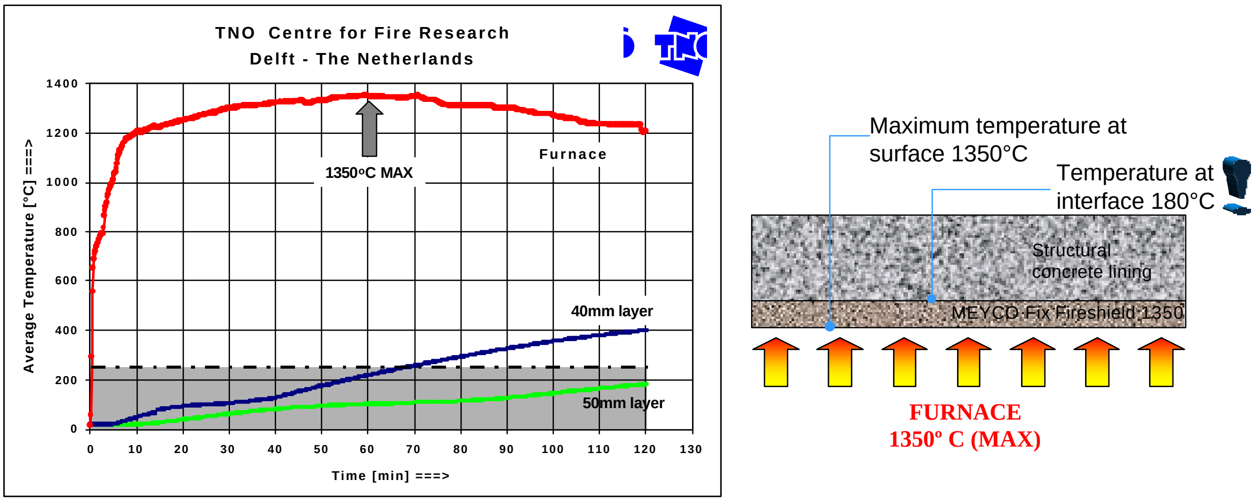


Figure 16: Time-temperature curves for Fireshield 1350, TNO Test Centre, Netherlands

As can be seen from Figure 16, testing of MEYCO® Fix Fireshield 1350 at the TNO Centre has shown excellent results with a layer thickness of between 40 to 50mm producing very low interface temperatures of below 225ºC at 50mm thickness, and below 400ºC at 40mm thickness. No spalling was observed on any of the test panels, as the example demonstrated in Figure 17. TNO consider that 225ºC is the most onerous requirement to date.

Figure 17: No spalling of passive fire protection or structural concrete observed on test panels.

13 Conclusion

1. To achieve durable sprayed concrete linings, the development of the concrete mix design is only but one facet that needs to be accomplished. The production of durable sprayed concrete is significantly reliant on human skills during spraying and equipment that is fit for the purpose.

2. The designer also has a key role to play. The important issues in this case are to understand the sprayed concrete application process and not to over specify material properties. The key to achieving durability is through “buildable” by keeping details as simple as possible.

3. Wet-mix sprayed concrete applied using modern, high performance, environmentally safe admixtures and equipment equips the tunnel industry with an economical tool to construct permanent, durable single shell linings. The construction process has become highly automated thereby significantly reduces the degree of human influence that has, in the past, prevented clients from considering sprayed concrete as a permanent support.

4. Modern sprayed concrete specifications now address the issues of achieving a quality controlled modern mix design, providing guidance on promoting durability and effective execution of the spraying processes. As an example, the new European Specification for Sprayed Concrete (1996) produced by EFNARC, provides comprehensive systems to attain permanent sprayed concrete.

5. With the increased use of durable sprayed concrete linings, new technologies to promote and maintain their use have entered the market recently. These systems enhance watertightness and provide high performance fire resistance.

6. Further implementation of durable sprayed concrete for tunnels and other civil engineering structures is increasing, with a marked change during the mid 1990’s. This trend is set to increase further as design and construction teams become more familiar with modern sprayed concrete technology, and the durable concrete that can be produced.