Muir Wood Lecture 2022

Wet-mix Sprayed Concrete: A Modern Support Method in Tunnelling and Mining

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N° ISBN : 978-2-9701436-6-6

JULY 2022

ASSOCIATION INTERNATIONALE DES TUNNELS ET DE L'ESPACE SOUTERRAIN
AITES
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INTERNATIONAL TUNNELLING AND UNDERGROUND SPACE ASSOCIATION

Muir Wood lecture 2022 - **Wet-mix Sprayed Concrete: A Modern Support Method in Tunnelling and Mining**
N°ISBN : 978-2-9701436-6-6 / JULY 2022
Layout : Shoot The Moon – Avignon – France – https://www.shoot-the-moon.fr

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Tom Melbye is the Senior Consultant and former President of Normet Group, joined Normet in 2007 after a long successful career with BASF Construction Chemicals. He has over 40 years of international experience in underground construction, both as a contractor and as a supplier of construction chemicals and equipment. Tom Melbye is active in creating and furthering new technologies, and is considered among the leading persons having driven the development of wet-mix sprayed concrete from its first uses in the late 1970's, to the latest modern processes for constructing safe and economical processes the industry benefits from today. Melbye has developed patents for two revolutionary product systems in 1992 and 1993. Tom Melbye also is a pioneer in using pre-excavation grouting as a method for effective waterproofing and stabilization of rock tunnels. In 2007, Tom Melbye received the Golden Hammer Award from the Norwegian Rock and Blasting Association for his outstanding promotion and development of Norwegian Tunnelling technologies and sprayed concrete internationally. In 2015 he was honored to become Hall of Fame of Mining together with Normet team for development of use of modern sprayed concrete for ground support in mining worldwide. He has been speaker and presented a number of papers worldwide on conference on the topics of Ground Support and use of Sprayed Concrete Since 1992 he has been an active member of EFNARC (European Federation for Specialist Construction Chemicals and Concrete Systems) and has served four years as the President of the federation. Using his experience and expert advice, Tom Melbye has significantly contributed to the development of the international tunnelling industry by being an Executive Council Member of the ITA (International Tunnelling and Underground Space Association) from 2011 to 2015. Melbye is one of the founding and active members of ITAtech, acting as Chairman ITAtech Activity Group on Lining and Waterproofing and member of ITAtech Steering Board from 2011 to 2014. Tom continues as a Member of the ITA Tunnelling Awards Committee and Judge in 2015, 2016, 2017 and 2018

«I *would like to express my thanks to ITA-AITES for giving me the opportunity to present and share my experiences, enthusiasm and key developments of sprayed concrete during the last 45 years I have been in the industry.*
The author would like to particularly thank Ross Dimmock and colleagues in Normet for their excellent support and valued inputs to this paper. Furthermore, I am grateful for the excellent inputs and ideas from past colleagues in BASF, Meyco, Rescon and T. Furuholmen.»

>> Abstract

One of the key developments over the last 40 years in both the tunnelling and mining industries has been with the application of sprayed concrete for ground support. Sprayed concrete, a globally recognized support system in underground projects, is required to perform its support function not only over the expected life of underground openings but also, from a safety and productivity perspective, at a very early age. The balance between placement ability, early strength and long-term performance is a delicate one, and has been repeatedly improved upon as the use of sprayed concrete has increased in mining and tunnelling. Early strength is particularly important in safeguarding the integrity of underground openings on the one hand, as well as in protecting the operators and equipment on the other, thus allowing work resumption as quickly as possible while strictly following all safety regulations. The main developments have been in much improved overall safety, up to a 6-fold increase in spraying outputs and vastly improved quality, which nowadays matches that of standard concrete. These improvements have been mostly brought about by the introduction of wet-mix sprayed concrete from the mid 1980's onwards, with robotic spraying machines operated by highly professional nozzlemen. This new modern high performance sprayed concrete approach, coupled with new waterproofing methods and smarter, holistic tunnel design approaches, affords the industry some significant steps forward in faster, more environmentally friendly and lower cost and lower risk tunnelling. In addition, the single shell sprayed concrete method in combination with electrically driven spraying robots offers big savings in CO_2 output. This paper covers the history of wet-mix sprayed concrete, showing its development and the actual state-of-the-art, and including future insights with respect to best practices and technologies which form the basis for the safest, earliest re-entry policies and with a holistic approach to mix design, equipment and application techniques. One of the future trends and opportunities will be the removal of the operators away from the tunnel face through the use of automatic remotely operated spraying robots equipped with a 3D scanning system; this also allows obtaining real time information on all parameters of the spraying application (IOT solution). Simulator supported user training of High-Performance Sprayed Concrete is crucial in ensuring the correct level of operator qualification in the future. Here the ITA/ITAtech will play an important role. Other trends in future developments discussed include the development of cement-free sprayed concrete linings using geo-polymers that offer a new dimension in material performance in terms of enhanced durability and improved environmental credentials.

KEYWORDS : Wet-mix, sprayed concrete, geo-polymers, tunnelling, mining, sustainability, robot.

1 >> History of Sprayed Concrete

All construction projects, particularly underground construction projects, are unique. The contractors and suppliers need to be very adaptable and flexible as any underground project contains a fair number of unknowns, which impacts multiple portions of the project. Sprayed concrete materials, equipment and application know-how have improved greatly over time. The modern wet-mixed sprayed concrete has widened the applicability – enabling use of sprayed concrete in projects, which were not possible before.

Sprayed concrete used to have a bad reputation and was considered as dirty and low-level work. Although the perception has changed in many countries, there are still a lot of countries and projects where sprayed concrete is seen as a low-level work of a low quality. One reason is that sprayed concrete has been, in many cases, seen as temporary work. I will in this paper share my 40 years of practical experience working with and using wet-mix sprayed concrete.

Sprayed concrete, or Gunite is not a new invention. Sprayed concrete (mortar- Gunite) has been known for more than a century. The first sprayed concrete jobs date back to 1907, (refer Figure 1). The jobs took place in the United States by the Cement-Gun Company, Allentown. Carl Ethan Akeley invented the first device to spray dry materials for new constructions in Pennsylvania in 1907. He needed a machine and method to spray onto mesh to build dinosaurs. His company, the Cement-Gun Company, protected the brand name "Gunite" for their sprayed mortar. This mortar contained fine aggregates and a rather high percentage of cement.

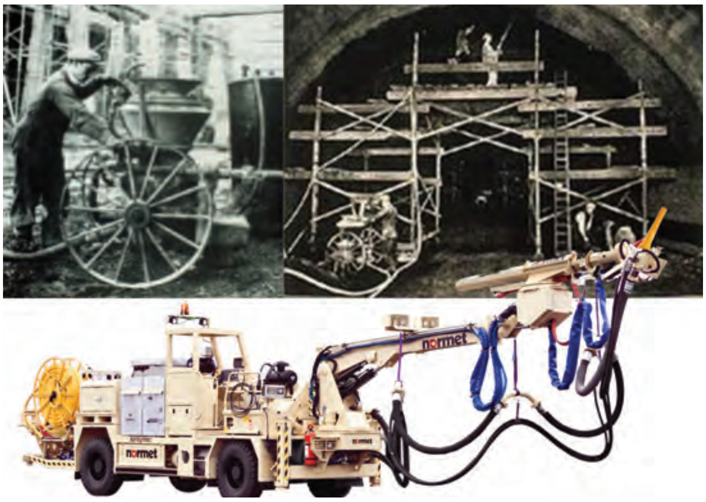

Figure 1: Development of sprayed concrete equipment – from Akeley gunite machine (pressurised pot) to todays spraying robots (melbye 2006)

The name Gunite is still in use to avoid this confusion between sprayed mortar (Gunite) and sprayed concrete, the expression "Sprayed concrete" is used for every sprayed mixture of cement and aggregates above 4 mm. In many English-speaking countries sprayed concrete is also referred to as "Shotcrete".

There are two application methods for sprayed concrete:

1. The dry-mix method
2. The wet-mix method

Originally all sprayed concrete was dry mix. In dry mix the dry mixture of cement and aggregates is filled into the machine and conveyed with compressed air through the hoses. The water needed for the hydration is added at the nozzle and often together with accelerator. There are applications for dry-mix machine today, especially in the refractory and concrete repair industry.

The modern dry spraying pump was developed in the late fifties in Switzerland with rotor machines from Meyco GM /Piccola or Aliva. Today, the pumps remain similar to those manufactured in the late fifties with only minor modifications and improvements. Dry mix is also used for rock support in mining and for slope stabilisation in developing countries. However, the major use today is in refractory industry, repair work and spraying of swimming pools or similar constructions.

High capacity robotic applied wet-mix sprayed concrete with fibre reinforcement has been the standard method for rock support in Norwegian tunnelling since the late seventies. The innovation history is not well-known in the industry. Some people claim that the development of the "high capacity robotic applied wet-mix method" started in Norway, while others claim that Norwegians also had a strong influence on how the method developed around the world.
The challenge is Norway is topography (mountains and fjords); establishing roads between areas and islands where people settled. Demand for efficient excavation and rock support enabled tunnel construction in many places. Simultaneously, cost-effective tunnels were needed to utilise the hydro power potential. Later on, the experience was utilised for construction of infrastructure tunnels including subsea tunnels and caverns for storage of oil and gas from the reservoirs in the North Sea. The "domestic" know-how in underground space had multiple uses.

Two of Norway's largest civil contractors Høyer-Ellefsen AS and Thor Furuholmen AS both recognized the advantages in developing the use of sprayed concrete for rock support as a replacement to cast in-situ concrete linings. There is no doubt that the "race" between these two very competent contractors led to the innovations and rapid development and use of the wet-mix method in Norway. (Refer Figures 26, 27, 28 and 29).

The development in the wet-mix method in Scandinavia between 1971 and 1980 meant a complete change in the market. During this period the sprayed concrete market changed from 100% dry-mix spraying to 100 % wet-mix spraying. During the same period a similar change from manual to robot application took place. This dramatic change is unique to Norway. Since about 1976 to 1978 silica fume and steel fibres have been added to wet-mix sprayed concrete. It is fair to say that "Norwegians led the way into real wet-mix sprayed concrete".

1 >> History of Sprayed Concrete

Norwegians are the ones with the longest experience and most in-depth knowledge about use of wet spraying. In the seventies wet sprayed of poor quality was produced. This was due to poor equipment and little knowledge of the method. A very high-water content was used to enable adequate flow of the mix through the equipment. Water to cement (w/c) ratios were up to 1.0. During the construction of oil platforms in the seventies and eighties the quality standards were improved. The improvement was achieved by using some new superplasticiser and concrete technologies that allowed low and controlled w/c ratios combined with high flow and slump. Nowadays wet-mix sprayed concrete can be easily produced with compressive in-situ strengths of more than 60 MPa at 28 days.
Wet sprayed concrete used as single shell method was introduced in Norway in the late 1970's in road, subsea and water tunnels, and in hydropower projects.

The push for innovation in Norwegian tunnelling industry in the seventies and eighties combined with customers and contractors investment into testing development of mix design, new materials, equipment and operator training meant that the sprayed concrete work became one of the most important and best paid jobs in the Norwegian tunnel industry – status retained until today.
Good compensation supported the recruitment of talented people. A positive circle was started, ensuring not only high production but high quality as well.

Unfortunately, I do not see today this type of encouragement and passion, where customers and contractors invest time and resources for innovation and testing of new materials and methods. In my view all major projects should have innovation and testing of new materials in the project as one of the tender's prequalification criteria. The whole industry and society will benefit from this innovation drive. Introduction of robots in wet sprayed concrete improved safety and productivity while reducing environmental impact. This was a major transformation from handheld application used in dry spraying. Use of robots increased capacity five-fold (20-25m^3/hour) in comparison to handheld dry spraying. High labour costs in Norway in the seventies combined with productivity requirements were additional significant drivers. Contractors were looking for alternatives to improve cycle times and move away from very time consuming and labour-intensive manual scaling of loose rock, (scaling several times during construction) and the use of cast in-situ linings combined with rock bolts. Additionally, the wet spraying method reduced rebound from >30% with dry spraying to <10% with wet sprayed robotic application which represented a significant cost saving as well. Major improvements took place with both safety and the working environment with less dust and no need to work under unprotected rocks.

Austria has been another leader in development and acceptance of use of sprayed concrete as an efficient rock support method with the New Austrian Tunnelling Method (NATM) developed from the late 1950's which has since been successfully implemented on many projects worldwide. The Austrian expertise in sprayed concrete led later to the introduction of the quality measure of early age strength – "J curves" and calibrated methods to reliably measure early age strength in order to have a standard for different rock conditions to avoid collapse in tunnels. The method was originally developed using dry spraying process, but it is now used for the wet spraying method as well. (Refer Figure 20). Today it forms the global standard for quality and design of sprayed concrete for rock support. The German speaking market was very slow to adapt to the wet mix sprayed concrete method and only end of the 1990's and beginning of 2000 the major new projects started to use this method.

Since the late 1990's, the United Kingdom has taken over the role from Norway to be the leading country in use of wet mix sprayed concrete. UK industry has introduced and developed new modern standards, QA and specification for use of High-Performance Sprayed Concrete. One key driver was the required industry changes needed following the Heathrow Express tunnel collapse in the late nineties. The wet-mix method has continued to grow with the design and construction of permanent sprayed concrete tunnel linings on the largest metro in Europe, London's Crossrail project, and several smaller transport and infrastructure projects recently.

As the adoption and acceptance of the wet sprayed method grew, demands for standards and specifications to ensure quality grew as well. EFNARC took in the mid-nineties a leading and important role to produce the first worldwide Guidelines and Specification for High Performance Wet Sprayed Concrete. The guideline contained clear criteria for mix design, material performance, quality assurance, testing and application. These guidelines and specifications are widely accepted and have been used globally, forming the basis of the European Sprayed Concrete Standard that was introduced in mid-2000 with EN 14487-1 and EN 934-5 (sprayed concrete admixtures and accelerators).

EFNARC has later developed and introduced the Nozzleman Training and Certification Scheme for trainers and operators of robotic wet sprayed concrete. This is a program endorsed by ITACET/ITA. The ITAtech has taken an active role in developing new guidelines and recommendations for new materials used in sprayed concrete and actively promoting use of sprayed concrete worldwide.
Wet sprayed concrete is today a widely used and accepted method for rock support in tunnelling and mining. Increasingly, projects are designed and constructed using a single shell lining with sprayed concrete due to the significant time and cost savings that can be achieved over standard traditional design approaches. Today we estimate that more than 15 million cubic meters of sprayed concrete is applied annually in tunnelling and mining operations. The estimated share of wet spray is over 70% per cent and growing each year.

2 >> Sprayed Concrete Ground Support

It is not the intention of this paper to present details of design approaches adopted for modern sprayed concrete tunnelling, but nevertheless the differences in the functionality and role of sprayed concrete ground support between hard rock and soft ground tunnelling applications is worth exploring to some degree. The basic concepts behind why 5-10 cm sprayed thickness functions in a 1000m deep base hard rock tunnel versus an excess of 30cm sprayed concrete lining is needed in metro project less than 30m deep in soft ground. Clearly, sprayed concrete ground support acts differently in these significantly differing tunnelling environments.

2.1. HARD ROCK TUNNELS

Figure 2: Sprayed concrete for hard rock tunnels. Development of a rock arch to support the opening

Of importance in tunnelling is the speed of installation of the sprayed concrete rock support following excavation rounds, be it by drill and blast or road header or even a TBM. Early preservation of the inherent strength of the rockmass is imperative for effective, active rock support. The early application of even the thinnest sealing coat of sprayed concrete has enormous benefits to the tunnelling team, that are not easily defined by the most complex 3D finite modelling, but these benefits we have seen from experience, and can be summarised as follows:

- A thin sealing coat of sprayed concrete applied to the rock surface is “squeezed” into the freshly exposed rock fissures and joints and “seals” them from the air, coupled with immediate bonding to the rock surface helps keep the newly exposed rock surface intact. At this very early age, sprayed concrete has very little structural strength and the primary function of the sprayed concrete at this time is to seal the ground an minimise the movement of groundwater within the ground, thus enhancing the inherent stand-up time rather than providing any mechanical support.
- This sealing layer prevents small blocks from becoming loose that would perhaps leading to unravelling of adjacent blocks, thereby enhancing stability under what is familiarly referred to as “key block theory”
- This thin layer creates a myriad of mini sprayed concrete arches immediately that are all cumulating in a uniquely macro stabilising system, that are collectively adequate to prevent larger rock blocks of up to 2 tonnes from loosening
- This early behaviour is often underestimated and still proves quite difficult to quantify the performance so far in our industry. However, these very young age sprayed concrete characteristics are certainly advantageous in rock face stability.

As indicated in Figure 2, 5 to 10 cm of structural fibre reinforced sprayed concrete, typically coupled with permanent rock bolts or anchors works and interacts together with the surrounding rockmass to form a very effective and strong “structural” rock arch capable of supporting the opening for both long term ground and water loads. The philosophy behind this rock arch development has a number of authors, but for the purpose of this paper we refer to it as the Fenner-Pacher Curve (simplified in Figure 3), developed from the great Austrian designers during the late 50s and 60s for deep tunnels in the Austrian Alpes and their subsequently successful New Austrian Tunnelling Method (NATM). Needless to say, the same rock behaviour and support approach is the same regardless of nation and the Norwegian Tunnelling Method (NTM) developed too along similar approaches based on the understanding of the rockmass qualities, and by example, Barton’s Q-System (Grimstad & Barton 1993, NGI 2015) demonstrates similar rock support and reinforcement requirements for rock tunnels. All approaches consider the quality of the rockmass and are based on sprayed concrete and rock reinforcement being used to actively control ground movements, or “mobilising the inherent strength of the ground” like a brick arch, to form a competent effective rock arch around the tunnel opening.

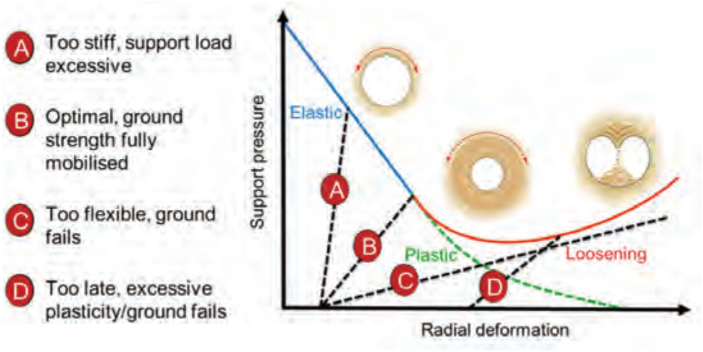

Figure 3: The Fenner-Pacher Curve simplified to demonstrate rock support interaction behavious in rock tunnels (Fenner 1938 and Pacher 1964)

The Fenner-Pacher Curve is a good tool to help understand the mechanisms to simply describe ground-support interaction. It shows what is good practice, but importantly, the understanding of sprayed concrete placement timing after excavation coupled with the strength, and thus stiffness, of the support system. In essence, for efficient sprayed concrete support Line B in Figure 3 is optimal. This support is installed soon after excavation and the stiffness of the support allows radial deformation of the rockmass and thereby permitting the development of a rock arch. If the spraying of the ground support was too late (Line D), or too soft (Line C), then the rock mass would move too much and instability normally ensue, which ends up being either very expensive to rectify, or disastrous with a collapse situation! It is therefore required in designs, that both the early age sprayed concrete material properties combined with their long-term durability performance are specified and validated in trials and continuously monitored and reviewed as works progress.
The unique beauty of sprayed concrete material is that it “matures” dynamically with time to fulfil the rock support needs of the tunnel. Sprayed concrete develops in strength from the point of spraying as an immediate relatively firm material having a strength of say 0.1MPa, then at an hour of 1MPa, and continually developing strength up to 50-70MPa at 90 days. This progressive early age to mature strength development works in sympathy with the need for radial closure of the rock mass, controlling the movements and developing the rock arch along with other rock reinforcement elements.`
`

One critical and often unwelcome factor in tunnelling both the tunnel team and the sprayed concrete material itself is the encountering of large volumes of ground water ingress during the tunnel drive. To meet this often unpredictable challenge, the Scandinavians in particular, have adopted and developed over the last 40 years the use of systematic pre-injection rock fissure grouting ahead of the advancing face. The use of systematic pre-injection using specially ground microfine cements brings excellent improvements in ground water control both during construction, but also to such low ingress levels that infrastructure clients consider it a viable permanent approach to reduce water ingress throughout the operational life of the tunnel. The degree of pre-injection grouting depends on the intended final use of the tunnel. For instance, in underground nuclear repositories or gas storage caverns, the permissible water ingress can be as low as 2 to 4l/100m/min, whereas road tunnels can be between 6 and 10l/100m/min.
The key components and processes that make this a successful system include, but not limited to those laid out in Figure 5.

Figure 4: Pre-injection drilling and grouting in Tunel del Oriente, Colombia

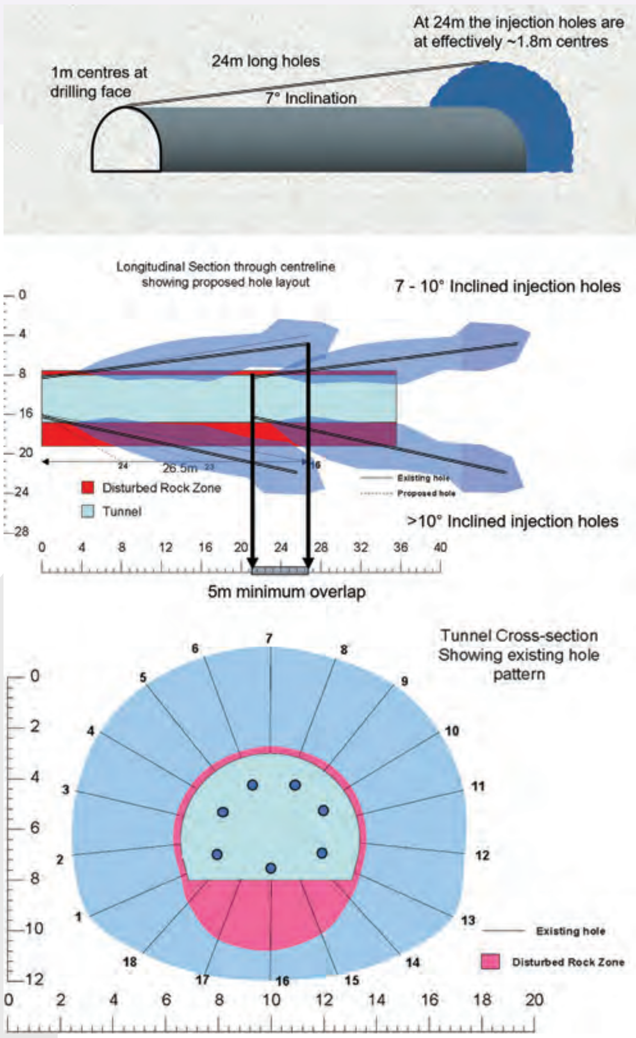

Figure 5: Pre-injection grouting generalised layout for rock tunnels

Sprayed concrete for hard rock tunnels is not only confined to drill and blast excavation methods, but equally has shown to be programme and cost effective when adopted behind the cutter head of hard rock TBMs with purpose built spraying rigs. One of most recent examples of this approach was for the deep alpine Gotthard Base Tunnel, Lötschberg in Switzerland as presented in Figure 6.

Figure 6: MEYCO Sprayed concrete robot running on ring beam behind TBM cutter head on the Lötschberg tunnel site, Gotthard Base Tunnel, Switzerland (Source: Meyco)

2.2. SOFT GROUND TUNNELS

Most of the benefits and performance requirements of early age sprayed concrete are equally valid for soft ground tunnelling, particularly if the geology can be referred to soft rock, such as low strength limestones (e.g. chalk) and shales that benefit from rock bolting, where a small degree of radial closure can develop a ground arch. However, many soft ground projects are founded in cities that historically were located near rivers as a source of water and transport. This inevitably leads to the lithologies of urban projects being constructed typically through alluvial deposits and sandy clays etc, and ground arch development through radial closure/ deformation is both limited in nature due to the weakness of the ground, and undesirable, as ground settlement from tunnelling requires tight control to retain the condition of existing surface buildings and infrastructure.

Therefore, unlike in hard rock conditions, the design philosophy in soft ground tunnelling is to replace a rock arch with a sprayed concrete arch much as a retaining wall design (Figure 8), resisting all short and long-term ground and sometimes water loads, if not drained.

To achieve this, quite often a considerable thickness of high early age strength sprayed concrete is needed to provide a stiff support to the ground immediately after excavation. On many urban soft ground tunnel projects, the early age strength development design requirement is refined upwards to a stronger developing “J2 modified” target as used on projects in urban tunnel projects in Austria and the recent Crossrail project in London for example (as shown in Figure 20). Unlike rock tunnelling, soft ground miners look for sprayed concrete performance as defined by Line A in the Fenner-Pacher Curve in Figure 3. Typically, primary tunnel linings can be 20-40cm thick for 10m tunnels, up to 7 times thicker compared to rock tunnels as illustrated in Figure 7.

Figure 7: Circular geometry primary Sprayed concrete linings in excess of 40 cm thick for urban tunnels at 30m below surface (Source: Crossrail Ltd, London)

Additionally, excavation sequences are limited in advance length, the excavation faces often are sub-divided, such as with pilot tunnels or sidewall drifts, to permit faster incremental temporary ring closure, offering the advancing tunnel more stability and optimal ground movement control, thereby further limiting surface settlement effects. Water management in soft ground tunnel adopt a number of toolbox measures ranging from local injection with low viscosity chemical grouts, pre-drilled de-watering wells, or even if high risk, ground freezing to enable safe tunnelling to continue. The design approach for the long-term management of ground water ingress is predominantly achieved by installing preformed sheet membranes and in some cases by spray applied waterproof membranes where conditions and varying tunnel geometry of the tunnel lend themselves to this method, as indicated in Figure 8.

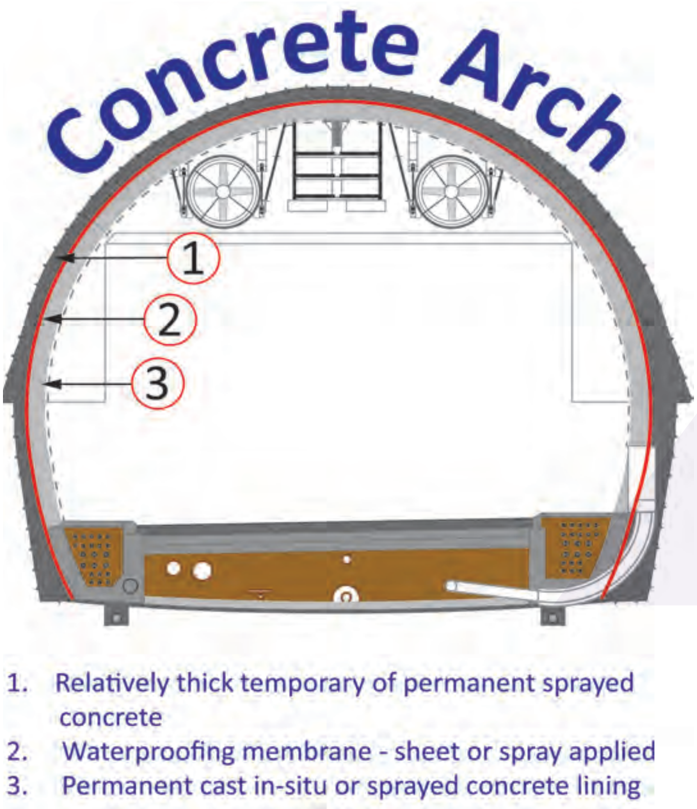

Figure 8: Sprayed concrete for Soft Ground tunnels. Development of a Concrete arch to support the opening

Typically, secondary linings are formed behind steel shutters with cast in-situ concrete, or if spray membranes are used, with sprayed concrete secondary linings. These secondary linings are equally as thick as the primary ground support sprayed concrete linings, and the industry is seeking new design approaches coupled with the much improved permanent sprayed concrete material performance to drive further efficiencies by slimming down the overall tunnel lining thickness, as discussed later in this paper in Section 8.4.

3 >> An Holistic Approach

Figure 9: Sprayed concrete tunnelling requires an Holistic approach, combining perceptive design, materials, machines and site competencies

Modern sprayed concrete application in underground structures is potentially the only construction method that needs an entirely wide-ranging holistic approach, combining high end material technology, equipment and people performance. There is the need to proactively respond to the changing demands during construction with all the elements of surprise Mother Nature presents underground teams, such as unstable, unpredictable geology, high levels of water ingress, or even coming across old buried structures from our ancestors!

From a materials point of view, sprayed concrete is technically a very high performing concrete, perhaps arguably one of the most demanding of all construction concrete materials. The underground construction industry demands excellence both in terms of the fresh state properties, but also, and increasingly so, the long-term material properties, as illustrated in Figure 24. In summary, the main demands for modern sprayed concrete can be characterised as follows:

- Long open time of the wet-mix to enable its transport, without losing performance, between batching plant and the sprayed concrete robot underground
- A suitable rheology of the wet-mix to ensure full filling of the pump cylinders to provide as low pulsation as possible during spraying
- A cement-set accelerator combination that works every time, delivering suitably high (and not too high), continuous early age strengths for ground support and production rates to be achieved safely by permitting fast re-entry time
- An increasing design demand for long term strength and durability to reduce lining thicknesses through design-optimised sprayed concrete linings, particularly in tunnels
- Skilled, accredited operators who are true craftsmen in the art of robotic applied sprayed concrete
- Modern state-of-the-art equipment, that delivers as close to continuous pulsation-free concrete spraying as possible, at output rates that meet the production and safety demands of the underground project. Equipment should record and deliver QC data via wireless LAN or otherwise to construction teams as part of quality control regimes.
- Design teams experienced and knowledgeable in both disciplines of efficient structural design with clear appreciations of the materials used and performance achievable with sprayed concrete, combined with the build sequencing and equipment used to effectively construct spaces underground with suitable face sizes. For holistic durability and safer buildability, structural designs will continue to reduce and remove steel reinforcement through tunnel profile optimisation to reduce bending moments, the increased understanding and more accurate modelling of 3D geometry effects, and the increasing use of structural fibres
- Good communication and decision-making processes with all stakeholders at sites, proactively responding to the performance of all aspects of the construction process and the necessary and timely design assessment of any changes required
- Effective on site HSEQ regimes that are resourced sufficiently, monitored, with feedback loops to design and construction teams so necessary actions are initiated in a timely manner

4 >> Sprayed Concrete is CONCRETE !

Some people consider sprayed concrete as a specialty concrete and that it is only be considered as a temporary support material. However, sprayed concrete is only one way to apply concrete. As with conventional casting techniques, sprayed concrete also puts specific demands on the concrete properties during application. At the same time, all normal technical requirements of concrete such as water/cement (w/c) ratio, amount of cement, correct composition, compaction (vibration) and curing must be observed. The reason why so much poor-quality sprayed concrete has been applied in many parts of the world is because people seem to forget that sprayed concrete is only a way of casting and that all concrete technological requirements must be fulfilled. Concrete technology is very simple and easy. On the old cement bags in Norway it was written – less water during mixing and a lot of water after casting.

The available best practice guidance for producing high performance robust wet sprayed concrete:

- Adequate total mix water content
- Cement
- Aggregates: 0-8 mm grain size
- Silica fume or nanosilica (colloidal silica)
- Admixtures: superplasticizers, hydration control and pumping aid
- Fibres: steel or polymer fibres
- Liquid alkali-free set accelerators
- Correct spraying equipment: pumps, dosing system, robotic arm, air/compressor and nozzle
- Correct execution: nozzleman qualification
- After-treatment: curing agents, internal curing/bond improver

4.1 ADEQUATE TOTAL WATER CONTENT

The water–cement (w/c) ratio has a large influence on strength and durability of concrete and sprayed concrete. Additionally, in sprayed concrete the w/c ratio has an impact on setting time, early strength, final strength and set accelerator dosage (Refer Figure 19). In sprayed concrete there was a conflict between properties of fresh concrete (workability with a high water/cement), and the need to have good set and early strength (a low water/cement) which led to reduced quality of the sprayed concrete final structure, as the high water content was always needed to pump. High performance water-reducing and hydration control admixtures, as well as silica fume and nanosilica, however, altered this for the better. In order to produce high performance wet mix sprayed concrete with good early and final strength, the w/c should always be < 0.45.

Less water – sprayed concrete requires a minimum of 185-200 litre water to have good consistency and open time. With lower water content there is the risk to lose workability quickly. To be on the safe side it is recommended to use **200 litre water/m^3 total mix** water (including the sand and aggregate moisture contents).

4.2 CEMENT

In order to meet the required w/c < 0.45 and approx. 200 litre water for the workability you would need to add 450 kg or more cement per cubic meter. Any lower amount can cause problems with workability, w/c and reactivity with the alkali-free accelerator. The reaction between the cement and alkali-free accelerator is essential for the early strength development in the sprayed concrete process.

4.3 AGGREGATES

As for all special concrete, the aggregate quality is of major importance for the fresh concrete as well as for the hardened product. It is particularly important that there are only minor differences in grain size distribution and other properties. Especially important are the amount and characteristics of fines, i.e. the grain size distribution and grain size analysis. However, it is irrelevant to talk about the choice of aggregate, as normally the available material must be used, and the recipe must be adapted to it. Nevertheless, for wet-mix spraying the maximum grain diameter must be 8-10 mm. Any aggregate with the size higher than 8mm will inevitably be in the rebound and not in the concrete layer. To achieve rebound under 10%, the maximum aggregate size must be 8-10 mm. This has been confirmed in many practical tests. Also, the concrete is much easier to pump and there is less risk for blockage when small diameter (65/80 mm) spraying hoses and nozzles are used.

Also, it is very important to assess the particle size distribution especially on the fines area. The fine material content in sieve size 0.125 mm should be minimum 4–5 % and not higher than 8–9 %. Too little fine material gives segregation, bad lubrication and risk of clogging. However, in the case of fibre concrete the surplus of fine material is important, both for pumping and compaction. A high fine material content will give a viscid concrete.

As the margins in the sieve basket are relatively small, two or more fractions has to be combined, e.g. 0–2, 2–4 and 4–8 mm, by adjusting the proportion between them, to make a sieve curve that fits within the ideal curve limits. Too little fine material will be compensated by using more cement, silica fume, new generation pumping aids, or viscosity modifier admixtures (“spaghetti effect” performance to fill the gaps in the grading). Too much fine material is primarily compensated by increasing the dosage of superplasticizers.

The recommended grain size distribution curve for the aggregate should fall within the grey area of Figure 10 (Modified EFNARC).

More and more crushed aggregate from the tunnel construction itself is used, even comprising up to 100% of the total aggregate needed. This approach normally requires a more robust mix design; higher cement content and higher dosage of super-plasticiser.

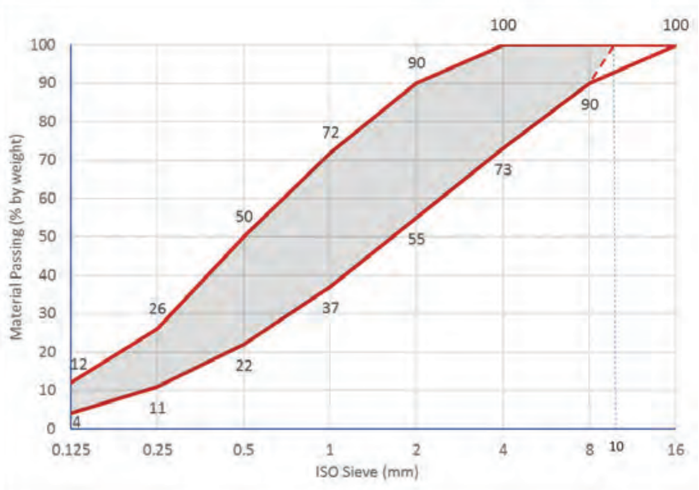

Figure 10: The grain size distribution of aggregates for sprayed concrete should be inside the Envelope (Modified from EfNarc 1996)

Crushed materials must be tested for any contamination or impurities that can have a negative impact on the concrete quality e.g. mica or clay. Aggregate taken out from the seabed needs to be properly washed before use to prevent chlorides entering the concrete mix. Chlorides have negative effects on the properties of both fresh and hardened concrete. Proper washing also prevents aggregates from sucking water out of the mix soon after mixing, causing workability loss of and the need to add excess mix water that inevitably leads to higher w/c's.

4.4 ADMIXTURES

In order to obtain specific properties in the fresh and hardened concrete, concrete admixtures should always be used in the wet mix spraying method. Concrete admixtures are not new inventions. The old Romans used different types of admixing material in their masonry, such as goat blood and pig fat in order to make it more mouldable. The effect must have been good, because the structures are still standing.

In fact, concrete admixtures are older than Portland cement, but only in the last 30 years stricter requirements for higher quality and production have speeded up research, development and usage. A major step forward in the development of new generation admixtures was taken in the building of oil platforms in the North Sea in late seventies and beginning of the eighties. In their construction superplasticisers were used on a large scale in advanced slip forming and high strength concrete (strength 80 MPa). Later the innovation of self-compacting concrete in Japan in the nineties brought new and more powerful superplasticiser technologies; the PCE type, to the market. Today, these form the basis for modern high performance wet sprayed concrete mixes. Water reducers are used to improve concrete workability and cohesiveness in the plastic state. The water reducer can give a significant increase in slump with the same w/c, or the w/c can be reduced to achieve the same slump as for a mix not containing the water reducer. The reduced w/c relates to a direct increase in strength. The higher slump increases pumpability.

As stated in section 4.1, the w/c is one of the fundamental factors in the concrete technology that needs to be under control. This is often forgotten with wet sprayed concrete.

As known to all, chemical admixtures and accelerators play key roles in sprayed concrete technology. The workability and flowability of the fresh concrete, as well as the setting and hardening behaviour of the sprayed concrete, are all parameters easily affected by chemical additives.

In order to keep the w/c at an acceptable low level (< 0.45) and to take advantage of the corresponding high concrete strength gain, it is crucial to use a water reduction admixture. However, the classic lignosulphonate-based water reducer will certainly slow down the early age strength development of the sprayed concrete. Lignosulphonates contain sugar, which is an extremely efficient set retarder. When this was discovered decades ago, melamine and naphthalene-based superplasticizers were introduced. Later, it was found that even these superplasticizers were not optimal for early strength development.

A common characteristic of these traditional plasticizers/superplasticizers is that they are all by-products (even waste materials) from the chemical industry. Approximately 25 years ago a new class of "hyperplasticizer" (PCE) was introduced in Japan for use in self-compaction concrete, and today this type is the preferred superplasticizer for sprayed concrete. There is a wide range of them; characterized as co-polymers based on polycarboxylate ethers , and they are tailor-made for different concrete applications. The water reduction capacity, slump retention property, etc. may vary a lot within this product group, on fresh concrete rheology and workability. PCE-based superplasticizers designed for sprayed concrete mixes have little if any negative effect on early age strength of sprayed concrete. (Refer Figure 11)

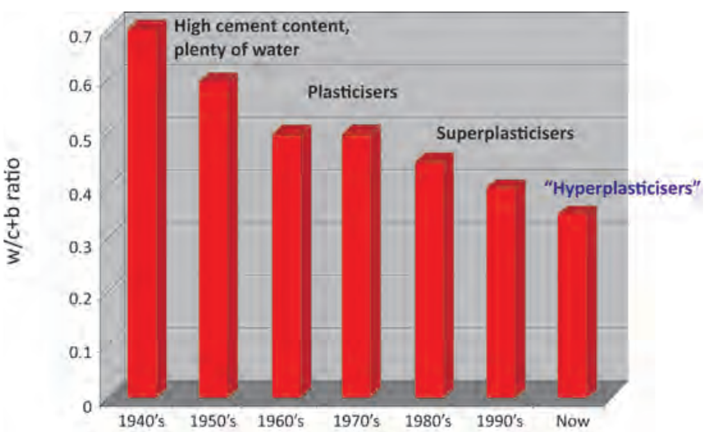

Figure 11: Historic development of water reducing admixtures and their water reducing capabilities

4.5. HYDRATION CONTROL ADMIXTURES

It is very important to be able to maintain the flow and workability of the concrete over longer periods of time before the actual spraying. Ideally, the fresh concrete workability should be unaffected, and no setting occurs until the cement hydration process is activated by the addition of set-accelerators added in the nozzle of the sprayer. Wet sprayed concrete normally has only a 1.5-hour pot life before it loses workability and cement hydration starts. Cement hydration starts when temperature in the concrete mix is raised by 2°Cfrom the lowest measured temperature. A common set retarder for concrete (typically based on sodium gluconate, a sugar-like chemical) is not the right choice for this application. Instead a hydration control admixture should be used. It was a revolution for sprayed concrete application when MBT launched the Delvocrete Hydration Control system in the nineties. This offered a new flexibility in logistics and use of wet sprayed concrete. It also ensured that workability and cement reaction was controlled for a long period of time and with no negative impact when it was sprayed and activated with set-accelerator added in the nozzle with the air. The hydration control system can keep concrete fresh from 4 up to 72 hours depending on the dosage of the admixtures. The system gives security and prevents expensive wet mix concrete from having to be dumped due to unexpected issues in the tunnel that prevents the wet mix to be applied. Delays can happen often as the conditions in the tunnel are difficult to predict and plan. It also gives flexibility in batching. The batch plant does not have to be open during night shift to produce few cubic meters of sprayed concrete.

The concrete can be brought to the site and stored in a concrete mixer there, so that an operator can take it for spraying when needed. In the cities where the traffic is heavy and space limited, concrete can be brought to the site outside peak hours and stored in an agitator and used when needed. This approach is often referred to having “Concrete on tap”.The hydration control system was first used successfully in the large Metro Athens metro project in 1991-94. All concrete was delivered during daytime and stored in agitator and spraying was performed around the clock, seven days a week. Afterwards the system has been used in numerous projects around the world. It is necessary to use hydration control in all wet sprayed concrete mixes to ensure workability, setting, early strength and final durability. It is a cost effective insurance approach that can give manifold savings. Today Mapei, Sika, BASF and Normet all offer hydration control systems, and they represent a standard admixture addition to mixes for most sprayed concrete projects.

Normal retarder (gluconate) should never be used in wet mix sprayed concrete. It has negative effect on setting and early strength or higher accelerator dosage will be needed to get the same result as with hydration control admixtures. The flexibility in the open time will be lost and wet sprayed concrete cannot be retarded for a long time. The next improvement in this technology was the development of a new hydration control admixture incorporating a dormant, secondary accelerator. The accelerator part is awakened in the nozzle of the sprayer when the concrete is mixed with the alkali-free accelerator. This idea was already discussed many years ago (Myrdal et al. 2001), and has now been introduced to the market and patented by Normet International Ltd. This product (TamCem HCA Plus) can boost the early age strength development of the sprayed concrete to new heights. Sprayed concrete tests using mixes defined in Table 1 included the performance of HCA Plus, and the comparison of gluconate, HCA and HCA Plus (all at equal set retarding dosages). The compressive strength values five minutes after spraying were obtained using a penetration needle according to BS EN 14488-2 (British Standards Institution 2006). The early age strength values are shown in Table 2. (Myrdal, Griffith 2014).

CONSTITUENT	AMOUNT (Kg/m^3)
Cement (CEM II/A-V 52.5N)	500
Sand (0–8 mm)	1,573
Water	200
Superplasticiser (TamCem 60)	3.5
Gluconate retarder /TamCem HCA/ TamCem HCA Plus	1.0/1.0 /5.0*
Alkali-free accelerator (TamShot 90AF, 8% by weight of cement)	40

* 5.0 = 1.0 (The retarder part) + 4.0 (the secondary accelerator part)

Table 1: Sprayed concrete mix design (water/cement = 0.40)

TYPE OF RETARDER/HYDRATION CONTROL	COMPRESSIVE STRENGTH (MPa)
Sodium gluconate	0.23 ± 0.02
TamCem HCA	0.36 ± 0.03
TamCem HCA Plus	0.55 ± 0.04

Table 2: Compressive strength values five minutes after spraying (BS EN 14488-2 (British Standards Institution 2006)

4.6. SILICA FUME AND NANO SILICA

Silica fume often also referred to as “Microsilica” is a waste product from the ferrosilicon alloy industry. It is a very reactive pozzolan and has significant advantages when used in sprayed concrete mixes.
Adding silica fume to a concrete give reduced permeability, increased sulphate resistance and improved freezing and thawing durability. When considering the properties of silica fume concrete, it is important to keep in mind that silica fume can be used in two ways:

- as a cement replacement, in order to obtain reduction in the cement content (usually for economic reasons).
- as an addition to improve concrete properties – both in fresh and hardened state.

In sprayed concrete, silica fume must be used rather as an additive than as a substitute for cement to improve the concrete and spraying properties. From a technical point of view, it seems beneficial to use silica fume at a level of 5-10% by weight of cement.

Because of the positive effects of silica fume, it should always be added to the sprayed concrete in order to obtain the best possible quality. Silica fume is very fine-grained and therefore when adding it to the sprayed concrete it is necessary to always add a higher rate of plasticizers / superplasticizers to disperse it. The dosage of admixtures increases by approximately 10-20 %, compared to sprayed concrete without silica fume. In sprayed concrete silica fume with > 92% SiO_2 content should always be used to get the full effect.

A new alternative to traditional silica fume was introduced in early 2000's; nano-silica (colloidal silica). It is an industrial product from the water glass/quartz sand production and comes as a liquid suspension. The production of nano-silica is well controlled, and it has very high SiO_2 content (close to 100%).

It is a highly reactive synthetic pozzolan that can be used in concrete to give benefits similar to those of silica fume.

As nano-silica has much smaller particle size than silica fume, the dosage can be reduced significantly. Nano-silica dosage can be just 10 - 30% of the dosage of silica fume, to achieve the same concrete properties. A significant benefit of the lower dosage is that nano-silica can be handled the same way as conventional concrete admixtures. Nano-silica has not yet been widely used in large scale engineering projects. There is not much documentation on its usage, and it is not yet covered by a harmonised European standard and therefore has not relevant CE marking. However, its benefits, specifically in resisting sulphate attack have been reported by Atahan & Dikme (2011), and Moslemi et al (2014). In addition, testing in Normet shows TamCem NanoSilica to be as effective against sulphate attack as GGBS (Ground Granulated Blast Furnace Slag) and silica fume.

4.7. FIBRES

Structural fibres were introduced in sprayed concrete in Norway in the late seventies by incorporating steel fibres into the sprayed concrete mix. In the latter part of the nineties, macro-synthetic polymer fibres were introduced to the market. Later, macrosynthetic fibres have been widely used in both mining and tunnelling.

Fibres are generally used to increase the toughness of concrete, which is specified by residual strength or by energy absorption capacity estimated from the load-deflection curve from a beam, round panel or plate test. They are also used to reduce or control cracking. Tests have shown that after hardening, the flexural strength of plain wet sprayed concrete was reduced to half due to shrinkage and micro cracking whilst fibre reinforced sprayed concrete maintained its flexural strength.

The advantages of fibre reinforcement in sprayed concrete have been proven in numerous projects and applications around the world. The technical performance of fibre reinforcement is generally equally good or better than traditional mesh reinforcement. Additionally, it is giving several other advantages:

- Overall productivity when applying on drill and blast rock surfaces is often more than doubled. It also eliminates a major bottleneck as it can easily fit into a development cycle with multiple blasts per day.
- Substantially improved safety, as sprayed concrete and reinforcement can be placed by remote controlled manipulator (nobody has to go below partly supported or unsupported ground to install the mesh)
- No poor compaction behind 1-2 layers of overlapping meshes. Poor compaction behind mesh causing very poor concrete quality and high risk of subsequent mesh corrosion and concrete cover spalling.
- The intended thickness and overall quantity of sprayed concrete can be achieved quite accurately and the problem of excess quantity to cover the mesh on rough substrates is avoided.
- One layer of mesh will be placed at varying depth in the sprayed concrete layer and cannot be placed in the cross section to target tension zones. The fibres will be present in the whole cross section, irrespective of where the tension will occur.
- Logistics advantage of avoiding handling and storage of reinforcement mesh underground

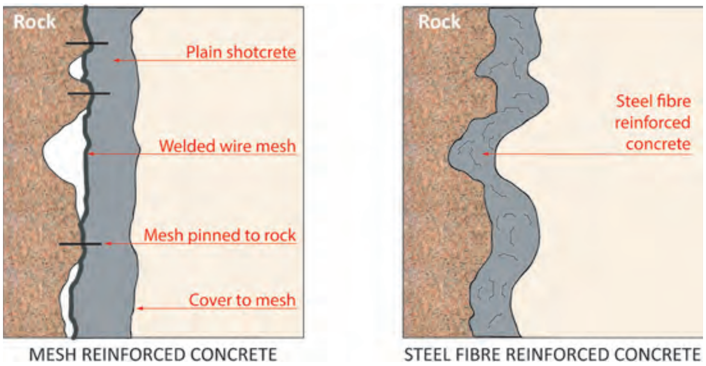

Figure 12: Comparrison between steel welsmesh and steel fibre reinforced sprayed concrete (Marc VANDEWALLE 2006)

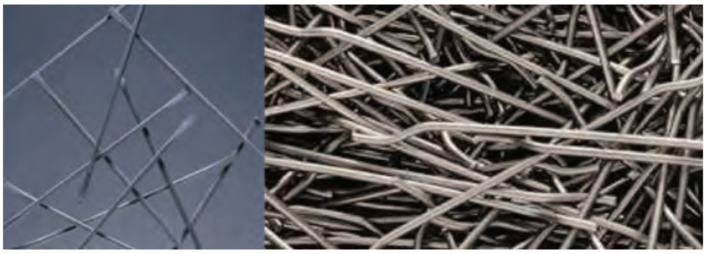

Figure 13: Typical steel fibres used in sprayed concrete

Steel fibres are currently the most commonly used fibre type in the sprayed concrete.

The fibre length should generally not exceed 60% of the pumping hose diameter depending upon the fibre type. To assist with pumping and spraying, the addition of silica fume is recommended to give optimal bonding between the steel and concrete matrix.

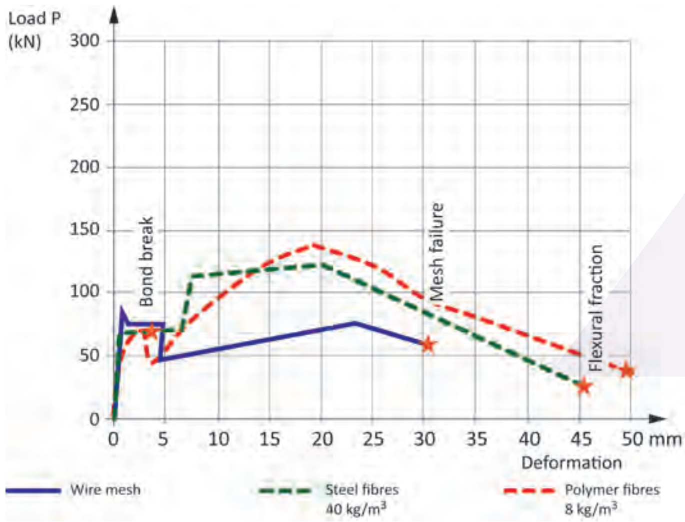

Figure 14: Typical behaviour of different kind of fibres compared to mesh in sprayed concrete (MELBYE 2006)

Macro synthetic polymer fibres

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

Fibre dosage rates are in the order of 5- 9 kg/m^3 of sprayed concrete versus 25-40 kg/m^3 of steel fibres. The synthetic fibres need to be made from high-class material to achieve final performance characteristics. Fibres are specifically shaped to resist matrix pull out which enhances the sprayed concretes performance even after cracks have developed.

Synthetic fibres are gaining popularity for the following advantages over steel fibres:

- Non-corrosive / non-magnetic
- Does not damage tires / injure personnel
- High performance polymer
- Weight ratio over steel fibres for transportation and dosing
- Load/deformation characteristics are better suited to mining requirements

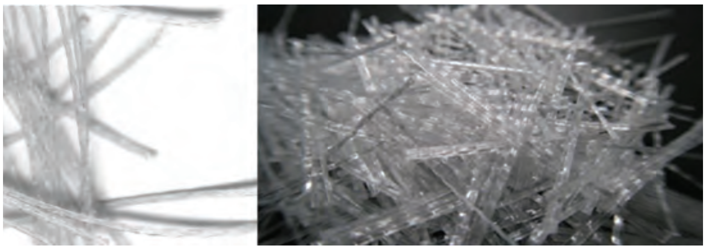

Figure 15: Typical macro polymer fibres used in sprayed concrete

Fibres have high material cost. In the wet sprayed mix design the cost is up to 30% of the total cost. Therefore, it is important to optimize the mix design and spraying to get maximal utilization of the fibres and meet the specified requirement with lowest possible fibre dosage. Fibre rebound can be much higher (up to 40%) than normal rebound if the mix design and spraying are not optimized. If this is not done the fibre dosage has to be increased and the costs will be higher. It is also important to notice that adding fibres reduces the workability and therefore the dosage of plasticizers must be increased. Also silica fume or nano silica has to be added to compensate for reduced workability.

Toughness in early age

The focus on ductility performance of fibre-reinforced sprayed concrete has been almost exclusively at 28 days and to a lesser extent at seven days after application. Very recently, research on the behaviour at a very early age (within a few hours after application) has begun. There is reason to believe that the performance of fibres can play a significant role at an early age when ground load may be at its peak.

The test results showed that especially polymer fibres had a high energy absorption after a few hours and before the sprayed concrete develops to high strength and get brittle. Polymer fibre gave much higher energy absorption values in early age than steel fibre concrete.

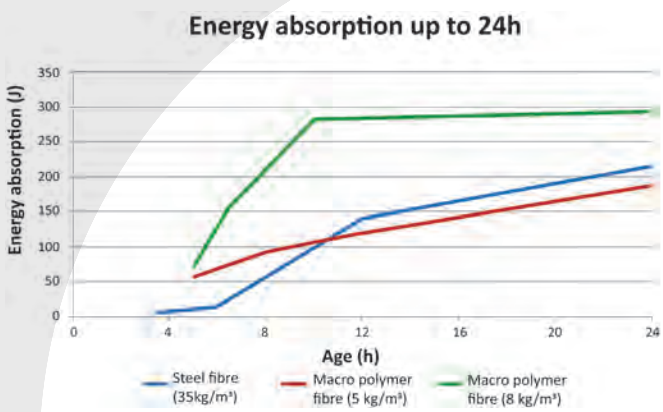

Figure 16: Energy absorption by fibre type (Test Propex Normet, Hagerbach Test Gallery 2017)

Monofilament polypropylene fibres

These fibres are normally used in the final coat of a sprayed concrete single shell lining to improve fire resistance and avoid spalling of the concrete during a fire. Typical dosage is 1-1.5 kg/m^3 depending on the fire loads defined and test panel results. (Melbye and Dimmock 2006).

Figure 17: Typical Monofilament polypropylene fibres

4.8. PUMPABILITY AND WORKABILITY

Sprayed concrete need min **slump of > 200 mm or flow (measured on flow table) > 550mm.** The high flowability is required to secure good pumpability and proper filling of the concrete pump cylinders. Due to the low workability there is the risk of improper filling of cylinders causing pulsation and layering in the concrete. Layering means that the concrete is not homogenous giving lower strength than specified, risk of spalling and leakage. Additionally, low workability increases the total consumption of accelerator due to pulsation (i.e. spraying only air and accelerator).

High workability i.e. flow or slump has nothing to do with high water content or w/c ratio.

Figure 18: Flowable sprayed concrete mix has over 550 mm flow measured on a flow table (Melbye 2006)

4.9. SET ACCELERATORS

To achieve fast setting with wet mix method accelerating admixtures has to be added at the nozzle. Currently the primary effect of these set accelerators is to reduce the slump (consistency) of sprayed concrete from liquid to paste while it is still in the air, so that it will adhere to the surface as the layer thickness increases. With the use of set accelerators, effective spraying on vertical and overhead surfaces becomes possible. The setting effect allows sprayed concrete to be used for initial support, which is an important function in tunnelling and mining.

Accelerators are added in liquid form via a special dosing pumps (piston, peristatic or rotor-stator (mono) pump). The accelerator dosage may vary, depending the type of accelerator, cement, the operator's skills, the surface and the w/c. High w/c's will increase the need for accelerators in order to reduce consistency. The classic accelerators for sprayed concrete have been water soluble silicates (typically sodium silicate i.e. 'waterglass') and water-soluble aluminates (typically sodium aluminate). Soluble sodium silicate provides rapid setting by reaction with calcium in the cement paste to form solid calcium silicate. With time the precipitate will form a hydrated calcium silicate gel somewhat like that formed by the hydration of C3S/C2S clinkers in the cement. Sodium silicate is still used some places in sprayed concrete technology, and is characterized by (Prudêncio 1998; Rixom & Mailvaganam 1999):

- Compatibility with most cements.
- Relatively low early strengths.
- Reduced final strength at high dosage, >10%

Sodium aluminates are far more alkaline than sodium silicates. These are highly caustic solutions which require caution in handling. Alkali aluminates react with several components in the cement (sulphate, calcium and C3A) to form ettringite and calcium aluminate hydrates and possibly other compounds. Issues related to sodium aluminate accelerators are:

- Health hazards associated with handling of highly caustic materials (a significant safety risk in underground mining).
- Addition of a lot of alkalis and the risk of promotion of alkali-aggregate reactions.
- Decrease in final strength.

These issues led to the development of non-alkaline accelerators (often referred to as alkali-free accelerators). The first liquid accelerator came to the market and in use in 1995/96 by Rhone Poulenc and MBT and was the biggest new invention in wet sprayed concrete since launch of fiber and silica fume in late seventies and hydration control admixture in the nineties. They are all weakly acidic (pH ~ 2–4) with aluminium sulphate as the main constituent (Bürge 2001), and typically formulated with additional non-disclosed constituents. A screening of the patent literature and the product data sheets from suppliers of alkali-free accelerators has shown that the typical ingredients found in these products are (Myrdal 2011):

- Aluminium sulphate.
- Aluminium hydroxide.
- Alkanolamine, e.g. DEA.
- Organic acids, e.g. formic acid.
- Fluorides.

Some of these alkali-free accelerators are transparent low-viscous aqueous solutions (all chemicals dissolved), whilst others are more viscous dispersions of tiny particles. Almost all alkali free accelerators on the market today are based on the same chemistry with only slight differences.

The flash setting behaviour of alkali-free accelerators is mainly caused by the reaction of aluminium sulphate with the lime in the cement forming ettringite, and then the following strength development is partly caused by the aluminium sulphate and partly by the additional constituents. The invention of alkali-free accelerators was big step to develop high performance wet sprayed concrete in terms of environment, work safety and durability. This accelerator showed no or low reduction in final strength as is the case with sodium silicate and aluminate accelerators. On the contrary it increases strength over a longer period as ordinary concrete. Long term tests from Jubilee Line in London showed that in-situ strength was increased from 60 MPa after 28 days to > 90 MPa after 1 year.

One major challenge is the introduction of blended cements (typically 20% replacement of Portland cement clinker with fly ash). Some of these cements develop strength quite slowly, therefore a specific ('tailor-made') accelerator is needed. Alkali free accelerator performance is also dependent on the w/c. Increase in w/c dramatically increases set time, gives lower early strength or requires higher dosage of accelerator as shown in Figure 19 below.

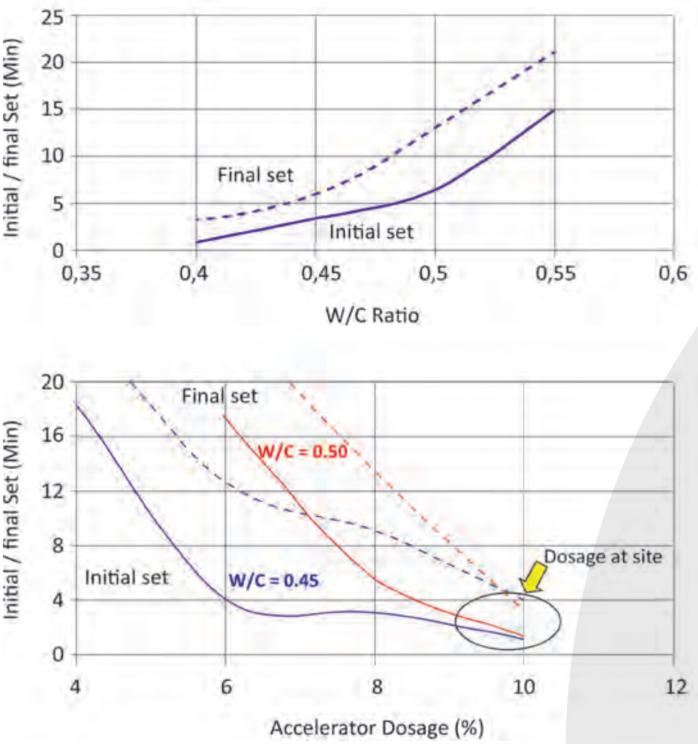

Figure 19: Influence of W/C ratio on setting time and accelerator dosage (ALDRIAN, MELBYE & DIMMOCK, 2000)

To date, not much development progress has been made since the first alkali-free accelerators were developed in late nineties. Basically, all manufacturers are using the same chemistry with only small nuances and modifications. The industry needs new types of accelerators that can withstand the poorer quality of globally used blended cement (less C_3A) and ensure fast setting, high early strength, good final strength and to take care of the durability. The goal should be to find an alkali free accelerator that works with all type of cements. The chemistry is available, but the industry needs to be willing to pay for it because the new type of accelerator will have 2-3 times higher price per kg than today's alkali free accelerators. But the final applied cost will be lower because of the lower dosage of accelerator, faster application, time savings and less problems with setting time and early strength.

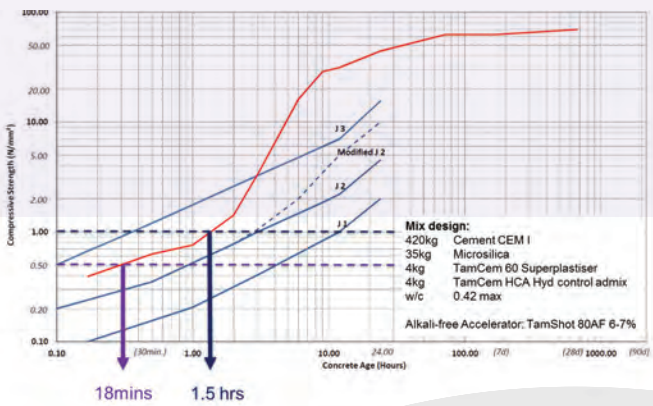

Figure 20: Typical sprayed concrete early age strength plot for Crossrail, London, showing 0.5 and 1 MPa early re-entry minimal strength requirements often specified for mines (RISPIN, MYRDAL, KLEVEN & DIMMOCK 2017)

Set Accelerator – Cement combination

Sprayed concrete is more sensitive to the cement quality than normal cast in-situ concrete. The application requires fast setting (in a split of second when accelerator is added in the nozzle) and high early strength development to be able to spray the required thickness and to develop early strength as fast as possible for safe re-entry into sprayed area without risk of drop out of newly sprayed concrete. A rule of thumb is that minimum 0.5-1MPa strength (measured according to the Austrian J curve; Figure 20) is needed for safe re-entry and to allow working under newly sprayed concrete. This safe early strength is normally achieved in 1-2 hours in normal temperatures with good quality cement and alkali free accelerators. It's also important that the sprayed concrete develops steady increase in strength in the first 24 hours in order to take increased load from the ground when the next advance/blasting takes place. A good sprayed concrete, when correct cement and reactive alkali free accelerator is used, should develop strength over 1 MPa per hour for the first 12 hours and also after that strength gain should be constant.

The recommended cement to be used is pure Portland CEM I – type 52.5 which gives best reaction with the alkali free accelerators

- fast setting and high early strength development. Blended cement types CEM II or CEM III are increasingly used for sprayed concrete. These cements give a challenge to achieve required setting and early strengths. Cement content and accelerator dosage has to be increased compared to the use of CEM I based mixes. Some of the blended cements have very slow setting and therefore they are proven difficult when used for sprayed concrete. As with 98-octane grade gasoline being needed for a sports car to accelerate and perform, the same is with sprayed concrete; The setting and early strength performance require a highly active clinker (like pure Portland cement).

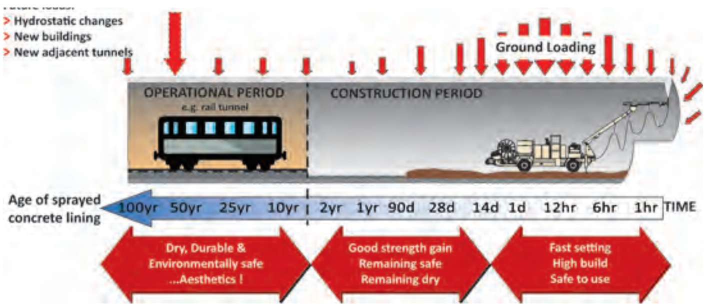

Figure 21: Loading behaviour on Sprayed Concrete Lining over time

It is important to do laboratory tests with the cement and alkali free accelerator to check the reactivity before final type and materials are selected for the mix. The first screening is done by simple Vicat mortar test as per Table 3.

Initial set	< 2 min	2–5 min	> 5 min
Final set	< 4 min	5-8 min	> 8min
6-hour strength	> 3 MPa	1–3 MPa	< 1 MPa
24-hour strength	> 15 MPa	10–15 MPa	< 10 MPa
Rating	good	acceptable	not acceptable

Table 3: Vicat mortar test criteria (according to EN 196, EN 480)

After this test and screening it is recommended to take the best combination of cement and alkali free accelerator and do a spraying pre-construction test to check the workability/pumpability and ability to spray required thickness overhead. Early strength and 28 days in situ core samples must be tested.

4.10. SPRAYING EXECUTION

In normal concrete it is important to compact the concrete well with use of vibration in order to have homogenous high-density concrete giving the required strength and durability. In sprayed concrete the nozzle and added air works as the vibrator to secure good compaction (i.e. density) and quality. Therefore, it is very important to have a well-designed nozzle and enough air supply. **For high capacity robotic wet sprayed concrete at least 12 m^3/hour with 7bar** is needed to ensure good quality and compaction. Any lower volume or air pressure will reduce quality (i.e. density, strength and durability. (Refer to Figure 44). Correct density for applied sprayed concrete should be in the range of 2.3-2.36 kg/dm3. Enough air and correct nozzle have a positive impact on reducing the rebound. This is opposite to the belief that less air gives lower rebound. Around the world the wet mix sprayed concrete is still sprayed with too little air and pressure resulting in low quality of applied sprayed concrete.

4.11. AFTERTREATMENT AND CURING

Sprayed concrete needs the same treatment as normal casted concrete. In construction it is always made sure that after placing concrete it is properly cured with sheets, water applied or curing agents. Aftertreatment and curing equally important to sprayed concrete but unfortunately very seldom done. Good bond and limited or no cracks are the most important parameters for use of sprayed concrete as rock support method. These affect also to the safety.

Tunnels and other underground construction projects present the worst conditions for curing of sprayed concrete as ventilation blows continuously dry (cold or hot) air into the tunnel. It can be compared to concrete which is constantly exposed to winds. One would think that tunnels have ideal curing conditions with high humidity (water leakage), no winds and no exposure to sun. However, this is not the case. Curing is one of the basic and most important jobs in sprayed concrete application because of the large cement and water content of the mix and the high potential for shrinkage and cracking of the applied concrete. Another reason is the danger of rapid drying caused by heavy ventilation, fast hydration of accelerated sprayed concrete and application of thin layers. Therefore, sprayed concrete should always be cured properly with an efficient curing agent. However, the use of curing agents has several restrictions: They must be solvent-free (use in confined spaces), they must not have any negative influence on the bonding between layers and they must be applied immediately after placing of the sprayed concrete.

The hydration of sprayed concrete starts in a very short time after spraying (in 5 to 15 minutes) due to the use of set accelerators and the curing agent has therefore to be applied within 15 to 20 minutes to protect sprayed concrete at this critical stage. Applying curing agents requires two time-consuming steps: Application of curing agent and cleaning / removal of the curing agent from the sprayed concrete surface between the layers if multiple layers are sprayed. The launch of a new type admixture in 1992 by MBT (Meyco TCC 735) opened a new way to secure proper curing of the sprayed concrete. Later Sika, Mapei and Normet have developed similar type of admixtures. These admixtures are also included in the new EN 934-5 standard as bonding improvers.

Bond improver (internal curing) means that a special admixture is added to the concrete/mortar during batching as a normal admixture. This admixture produces an internal barrier in the concrete which secures safer hydration and better resistances than the application of conventional curing agents. The benefits of this new technology are impressive:

- 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 very beginning of hydration.
- There is no negative influence on bonding between layers.

Because of this optimum curing effect, all other sprayed concrete characteristics are improved: density, final strengths, freeze / thaw and chemical resistances, water tightness, less cracking and shrinkage.

In addition, this technology has positive effect on pumpability and workability of sprayed concrete, even with low-grade aggregates.

It improves the pumpability of steel fibre reinforced sprayed concrete mixes, and the fibre orientation, thus reducing rebound and improving toughness values. A proven technology; the concrete bond improver technology has been tested and used with good results both in laboratories and on big jobsites. Comprehensive research programmes were carried out in Norway (SINTEF), in Switzerland (LPM Institute) and in Austria (University of Innsbruck). Bond strengths were higher than 2.0 MPa with failures discovered only in the concrete and not in the bonding area. Density and mechanical strengths at 28 days were more than 10% higher than in conventionally cured reference sprayed concrete.

Figure 22: Analogy to what happens to sprayed concrete without curing

4.12 STRENGTH TESTING

Sprayed concrete is concrete but mix design is more demanding. A lot of testing is needed to get the final mix design that meets the specific requirements. The success in wet sprayed concrete is based on a robust and good mix design and correct application.

Figure 23: Current best practice for early age sprayed concrete strength measurement – Proctor penetration needle and Hilti pull-out method

The strength grade of sprayed concrete shall be specified according to concrete strength classes C24/30 to C48/60 as specified in EN 206 (see Table 4).

CHARACTERISTIC STRENGTH (MPA)							
STRENGTH CLASS	C24/30	C28/35	C32/40	C36/45	C40/50	C44/55	C48/60
Cylinder	24	28	32	36	40	44	48
Cube	30	35	49	45	50	55	60

Table 4: Comprehensive strength classes for sprayed concrete (EN 206)

To determine that the concrete meets the requirements of compressive strength, the in-situ strength requirements given in Table 5 shall be met. The strength requirements are based on testing of a 50 mm diameter and 100 mm long core and include a 0.85 reduction factor to allow for effects of in-situ coring.

MINIMUM COMPRESSIVE STRENGTH (MPA)							
STRENGTH CLASS	C24/30	C28/35	C32/40	C36/45	C40/50	C44/55	C48/60
Core	20.5	24	27	30.5	34	37.5	41

Table 5: In-situ strength requirements for sprayed concrete

4 >> Sprayed Concrete is CONCRETE !

The best way to test sprayed concrete is to drill cores from the wall where sprayed concrete is applied. This gives normally more accurate results than cores drilled from sprayed test boxes. Nozzle angle and distance and compaction of sprayed concrete is better controlled when applying sprayed concrete to the wall. Also, the true picture of the quality and operators' skills are detected. When in situ cores are taken, the density of the cores is one parameter to be checked. This gives a lot of information if the spraying has been done correctly. Is enough air used, has the nozzle angle and distance been right and does the operator possess skills or not. Densities below 2.28 kg/m3 is a sign that something is wrong with application or concrete mix. Spraying into panels with a robot is very difficult and never gives the 100% correct or representative result. The spraying of the panel cannot be done with full spraying capacity and it is difficult to get the right nozzle angle and distance. With too short distance there is the risk to get rebound into the test panel which will affect the quality. For robotic spraying the size of the test panel must be at least 1m x 1m and the panel must be stable to avoid vibration. Spraying on panels 50 cm x 50 cm does not work and should never be done for robot spraying.

5 >> Durability of sprayed concrete

The application of sprayed concrete as permanent construction material has grown and at the same time the demand for its durability has increased. The use of traditional accelerators in high dosages has led to serious damaging impacts to the sprayed concrete, even within a short time after its application. The tunnel lining should remain 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 structure's exposure to environment during both construction and operation. Structural degradation normally occurs with unforeseen environmental changes. 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.

For sprayed concrete to be considered as a permanent lining material, either as a primary lining or a subsequent secondary lining inside a membrane system, it needs to be designed against three mechanisms that can negatively impact the durability of sprayed concrete, namely chemical attack on the concrete itself, steel reinforcement corrosion, and unforeseen ground movements such as from new adjacent future tunnelling activities or large building surcharges etc. (Figure 24 below)

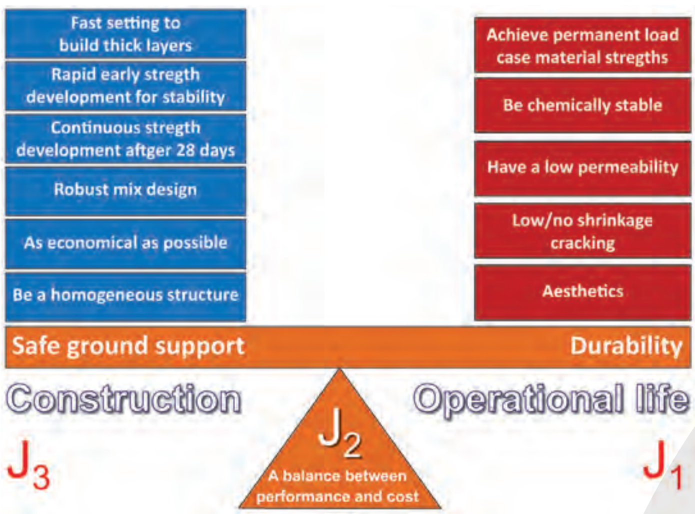

Figure 24: Parameters affecting sprayed concrete durability

5.1. SPECIFICATIONS AND GUIDANCE

Unfortunately, too often in the sprayed concrete industry, specifications and guidance documents tend to be" cut and pasted «for new contracts year after year, without much in-depth study of the current state of the sprayed concrete business. The recent advancements 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 (e.g. the EFNARC European Specification for Sprayed Concrete 1996, EN 11487-1, ITAtech reports and guidelines).

5.2. 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, quality control systems should be sufficient to control production. It is essential that communication between the design and construction teams is maintained from the pre-design phase to the completion of the project in order to advance the above processes.

Remember: "Wet Mix Sprayed Concrete is Concrete"

6 >> Spraying Equipment

6.1 HISTORIC DEVELOPMENT

Operating sprayed concrete equipment is one of the most demanding tasks in underground mining and tunnel construction. Experienced and skilled operators are becoming more and more difficult to find. The quality of the sprayed concrete application can vary significantly from one operator to another, hence finding skilled operators is critical, and the correct equipment for the specific purpose, and the need to develop equipment that reduces the impact of human influences on the final product.

Parallel to the material technology development there has been a constant innovative development in the equipment sector to produce machines suited for the new products and that are adaptable to the everchanging conditions in the construction business. The result is a wide range of machines that cover all sprayed concrete works: from huge tunnelling jobs with large quantities of concrete to be sprayed, down to small volume repair works. Independent of size and scope of the equipment, one thing is common: the tendency towards integrated and automated systems. Integration and automation ensure improved production output, consistent and controllable quality, as well as safer and more operator-friendly working conditions.

The first dry-method robot for commercial spraying was developed by Stabilator Sweden in the sixties. The robot was used worldwide on their projects. This was a major step in terms of increasing capacity, improving work safety and environment for the operators. The use of robots also improves the quality and reduces rebound and waste because a robot will not get tired, and positions the nozzle where it needs to be. Manual spraying is a tough and hard work. Manual spraying cannot be done with wet mix sprayed concrete because of the weight of the hose filled with concrete. Stabilator was the leading global company in sprayed concrete up to the seventies and increasingly developed sophisticated robots and delivery systems (e.g. Trixer unit to mix cement and sand in the tunnel) for dry spraying method. (Refer Figure 25)

Figure 25: Stabilator dry spraying robot from 1960s (photo Ola Woldmo)

When the wet spraying method was developed, and its use was started in Norway in the seventies the spraying was first done manually with a small ball valve pump Putzmeister P13 or KK215 (Refer Figure 26). It was soon evident that a robotic arm and another type of pump was needed to increase capacity, improve quality and the working environment.

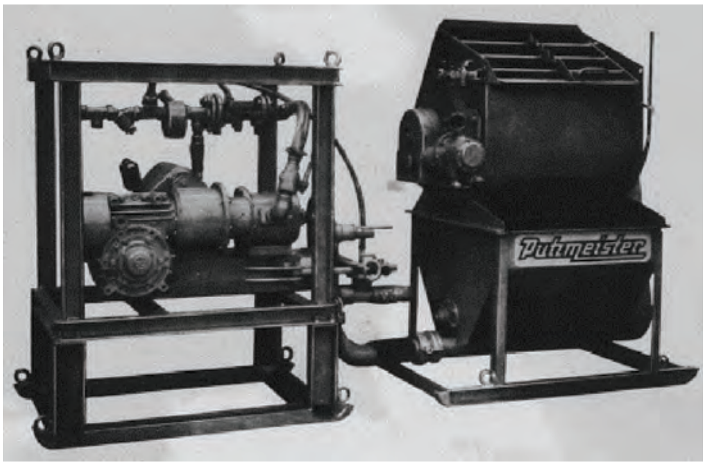

Figure 26: Putzmeister P 13 small ball valve pump used in Aurland, Norway 1971-77. (Photo Knut Garshol)

The first robotic arm was mounted on a normal tractor with a standalone pump on a trailer. The first integrated full compact robot was developed in Norway by the contractor Tor Furuholmen in cooperation with AMW (Andersen Mek. Verksted AS). It was used on a large wastewater cavern project outside Oslo in 1977. The robot arm was mounted on a Cat 944 carrier. A high capacity mono pump (capacity up to 20 m^3/hour– from Montanburo S8) was mounted on the back, and accelerator was fed to the nozzle from a pressure tank with a pressured air stream. Air to the nozzle was taken from an external system. (Refer to Figure 27) This robot could easily operate with an output capacity of 20m^3/hour with <10 % rebound. The results were revolutionary and a major step for wet sprayed concrete use in Norway. The robot was very sophisticated and ahead of its time. Later the robot has been updated and improved. Similarly configured spraying robots were developed by Putzmeister in the eighties.

Figure 27: Furuholmen spraying robot on a CAT 944 carrier from seventies. (photo: T. Furuholmen)

Another important player in the Norwegian sprayed concrete market was Hoyer Ellefsen and with their very innovative and forward looking engineer Hans Petter Thorsteinsen He developed in the early eighties very mobile robots based on truck chassis to be flexible and be mobile from site to site (Refer to Figure 28, 29). He founded his own branch inside Hoyer Ellefsen Robocon to develop and contract sprayed concrete. Robocon went outside Norway with its equipment and systems were sold to Chile, US, Israel and Saudi Arabia.
Robocon was the first company to integrate air compressor with the robot.

It was a race between Robocon and Furuholmen where I headed the sprayed concrete division to develop the best equipment and mix design. The Norwegian championship in sprayed concrete) was a competition that drove innovation in the industry and put Norway as the leading player in wet sprayed concrete and led to the use of fibers, silica fume and various new generations of admixtures.

Figure 28: The Robocon "cabriolet", the spraying robot from eighties based on truck chassis (O. Woldmo/Robocon)

Figure 29: Truck based Robocon spraying robot from nineties with a video camera to record rock (O. Woldmo/Robocon)

Putzmeister built a machine named "Buffalo" with two large booms and two concrete pumps on a crawler chassis for the major road tunnel project in Wurzburg, Germany. This was not a big success and was taken out of their offering. (Refer Figure 30).

Figure 30: Putzmeister Buffalo spraying robot with two separate robotic spraying booms and concrete pumps (Source Putzmeister)

6.2. STATE-OF-THE-ART SPRAYING EQUIPMENT

The trend recently has been to build complete and compact spray mobile machines for all types and sizes of tunnel and mining operations. The robots normally include fully articulated spraying booms, a compressor, concrete pumps, integrated dosing system, remote control and accelerators tanks. The addition of compressor is critical to guarantee high quality and low rebound spraying (<8%). With sprayed concrete a lot of air is needed in the nozzle to get compaction and dense concrete. Minimum requirements are 12 m3/min and 7 bar for high capacity robot spraying. Some suppliers promote spraying robots with 6 m3/min compressor. This is not sufficient capacity to produce dense and quality sprayed concrete and will result in more rebound. In Scandinavia today, most contractors use fully integrated and self-propelling spraying robots mounted on 3 or 4 axels truck chassis. These robots can be driven on normal public roads as a truck and are very mobile and flexible. They are equipped with low pulsation special designed sprayed concrete pump (such as Norstreamer) with integrated dosing system, 12 m3/min compressor, high pressure washing system, automatic hose and pump washing system, Reco Drive to move the truck using the remote control and with a long reach spraying boom, with smart spray systems to help the nozzlemen be more efficient. All the equipment is powered by the power taken off from the truck or via external electricity cable (hybrid system). Typically, these sprayers are operated by one person and have practical spraying capacity outputs of 25m3/hour with 5-6% rebound. An example is the Normet NorRunner launched in 2013 as shown in Figure 34. NorRunner is the longest reach sprayer in the world with 17m long reach. Lately Normet has developed for the

Japanese market a special sprayer and arch lifter in the same machine – Normet Zeus with 5 booms. These machines are in operation in Japan as shown in Figure 35.

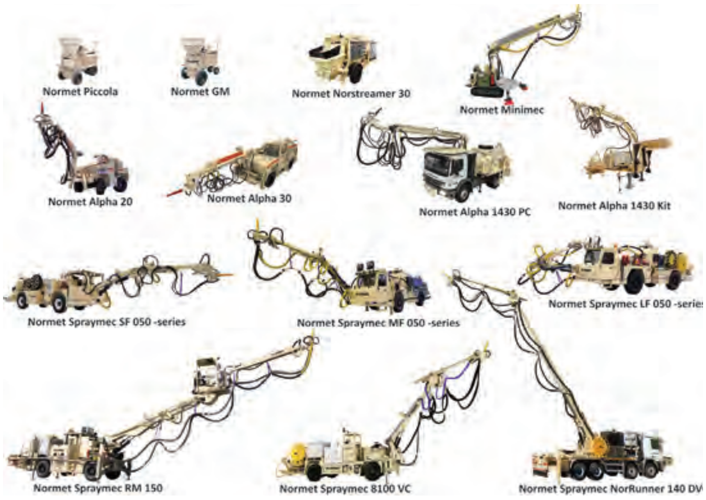

Figure 31: Normet spraying equipment for any type of tunnels in underground mining and construction

Figure 32: Modern Tunnelling sprayer- Spraymec 8100 hybrid with compressor 12m3 /min

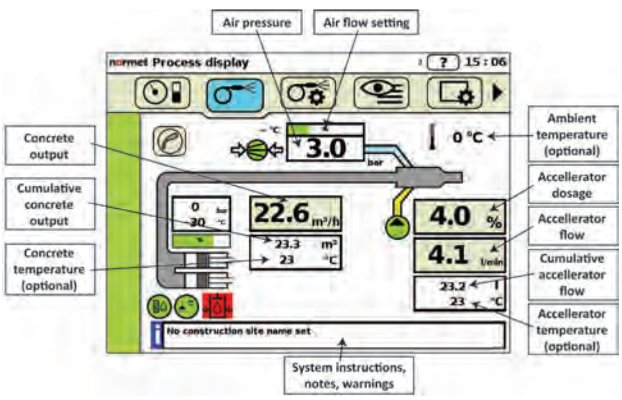

Figure 33: PIC Display –recording all of function of the spraying equipment and Pump

Figure 34: Normet Spraymec NorRunner 140 DVC is the biggest mobile sprayer in the world

Figure 35: Normet Zeus- 5- boom sprayer, working platform and arch-lifter in tests at the Normet factory before delivery to Japan

Figure 36 typical: Remote controls; wired and wireless. On top the wireless remote control for Spraymec with SmartSpray (Normet)

Different special application of sprayed concrete and equipment designs for shafts and hard rock TBMs (Refer Figure 37 and 38)

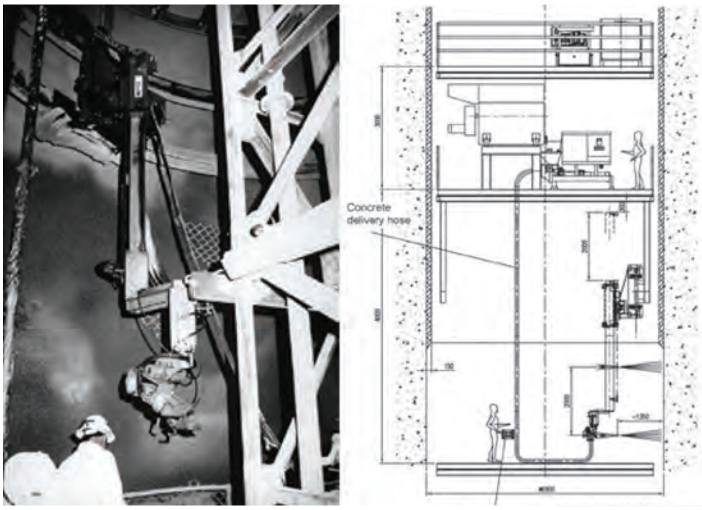

Figure 37: Example of a MEYCO® spraying manipulator for shaft sinking (Source Meyco)

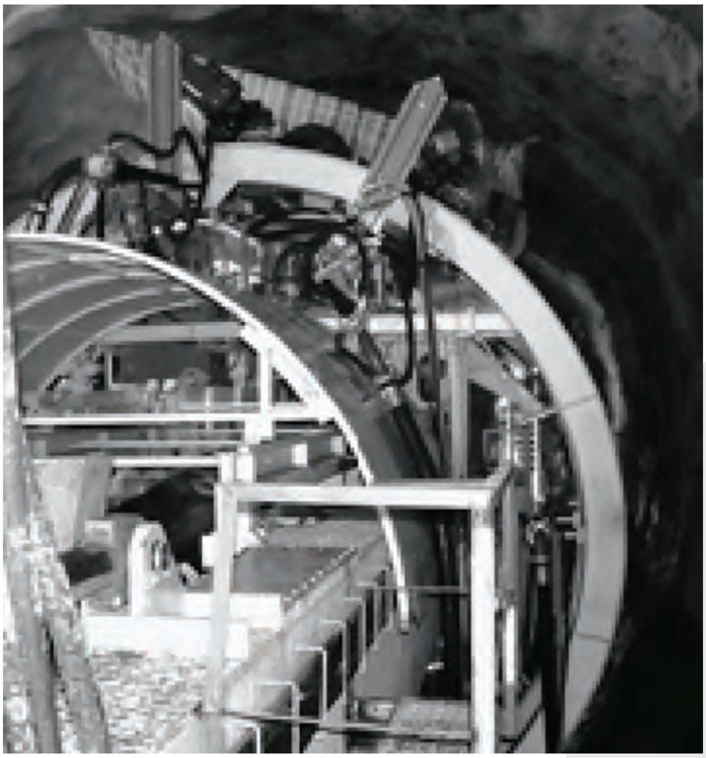

Figure 38: The MEYCO® Robojet spraying manipulator is integrated into a large diameter TBM (Source Meyco)

6.3. NEW DEVELOPMENTS

The target for equipment development is to ensure the quality of the sprayed concrete is to reduce the dependency on the skill of the operator – to improve both safety and quality. The SmartSpray System by Normet is a first step towards developing a spraying machine capable of fully automated sprayed concrete placement. Traditional control of a spraying boom means that every boom position and nozzle orientation is separately controlled by the operator to achieve the desired result. The spraying quality of concrete in place and even longevity of the machine can vary greatly between operators. The need for improved performance prompted Normet to design and build a fully automated spraying system. Normet's Spraymec family is currently available with SpraySmart System as an option. Current version includes two features to assist the operator—coordinated and point to-point control modes built on top of the standard boom control system—allowing the machine to be operated in either a semi-automated or traditional control mode.

With point-to-point mode, the operator defines a line between two points. Once activated, the spray nozzle automatically follows the defined line. If the nozzle angle is locked, it is automatically retained in position against the tunnel profile. The operator only has to move the boom to the next position needed for spraying. Nozzle position can be fine-tuned, and controls overridden manually if needed.
The next major step is fully automatic wet mix spraying system. Meyco, today part of Epiroc, launched the first fully automatic spraying robot in 2000 (Meyco Logica) and Smart Spray point to point spraying in 2003. The machine is equipped with a scanner and capable of spraying without any operator involvement. The system works based on the scanned data from the area to be sprayed. Once the machine has been positioned and stabilized at the required location, the spraying area is scanned. Automatic spraying is possible by defining the additional parameters of speed and row gap. The operator only has to mark the desired spraying area. The machine performs the spraying process fully automatically, at constant speed, spraying distance and angle along the surface. In order to override the automatic mode, the operator simply activates semi-automatic mode by using the joystick. As soon as the operator releases the joystick, the spraying process will continue in the automatic mode.

6.4 CONCRETE PUMP FOR WET SPRAYED CONCRETE REQUIRES A SPECIAL DESIGN

The concrete pump is one of the most essential and important parts of wet mix sprayed concrete application.

The professional applicators trust in double-piston pumps because of their robustness and high capacity in wet-mix spraying. To ensure even spraying, the latest equipment developments aim at producing a constant, pulsation-free conveyance of the wet-mix from the pump to the nozzle. Standard high output concrete pumps have a lot of pulsation produced by a long interval between piston strokes, with only air and accelerator being blown to the rock surface – without concrete. This results in banded concrete layers with low bonding and quality (not homogenous) as seen in Figure 40 and Figure 41 . High-quality sprayed concrete needs an even and homogeneous stream of concrete with minimal pulsation and maximum 30m3/hour in output capacity. Outputs higher than this cannot be sprayed in a proper and controlled manner. (Refer Figure 43) Normal concrete pump should not be used for wet mix sprayed concrete, due to big pulsation

By launching the Meyco Suprema in the early nineties, Meyco set a new standard via introduction of the first ever sprayed concrete pump with minimal pulsation. The pump has an electronically controlled push-over system that is integrated into the output adjustment. This arrangement minimises the pulsation of the material flow – hardly noticeable at the nozzle. An integrated memory programmable control system (PLC) supervises, coordinates and controls all functions of the machine. The PLC system allows checking and controlling of operational information (dosing quantity, concrete output, etc). The data can also be downloaded and analysed separately using Meyco DOSA TDC® data system. This system guarantees exact regulation of dosing relative to the spraying volume. In 2010 Normet developed and launched their own Norstreamer low pulsation pump with similar features, PLC control of concrete cylinders, integrated dosing system and new improved features like temperature control and measurement of concrete, air and accelerator temperature. This data is very essential to monitor setting and early strength. (Refer Figure 33, Figure 39 and Figure 41).

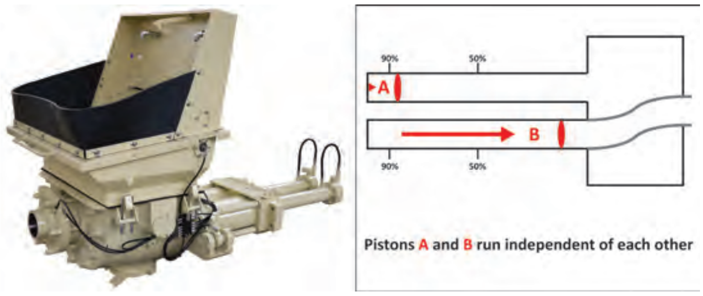

Figure 39: Normet NSP 30/40 low pulsation sprayed concrete pump with PLC and integrated dosing system for accelerator

Figure 40: Pulsation will result in layering effect in the applied sprayed concrete

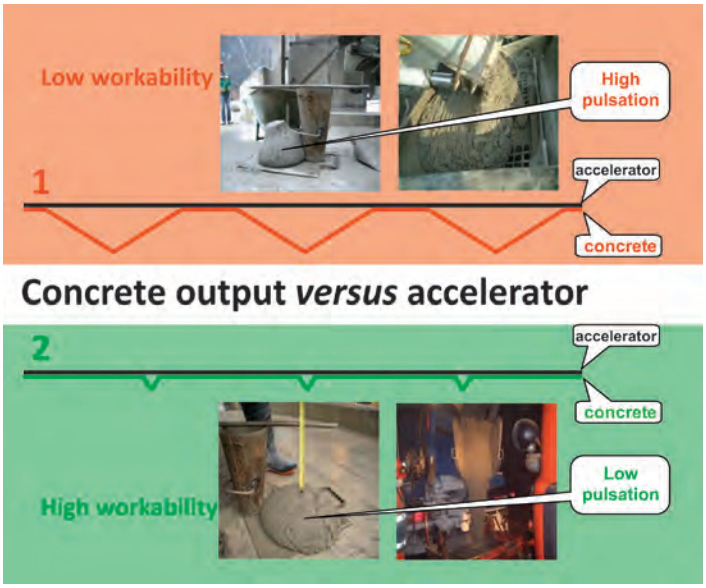

Figure 41: Low workability of sprayed concrete causes low filling ratio of concrete pump cylinders which results in high pulsation when spraying and therefore reduced quality and higher cost

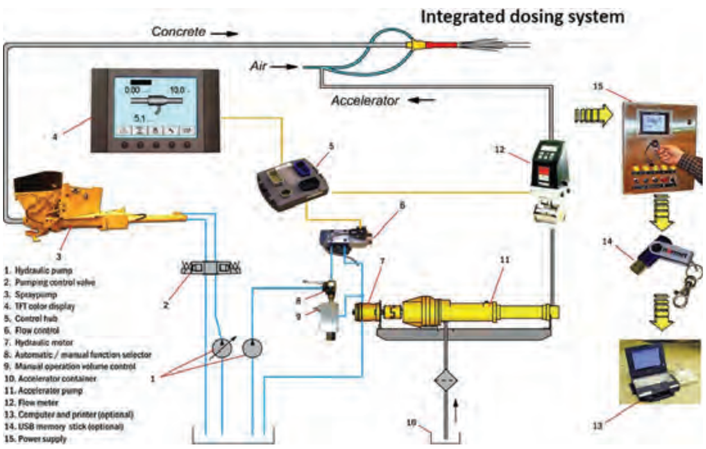

Figure 42: Integrated accelerator dosing system with storage of data

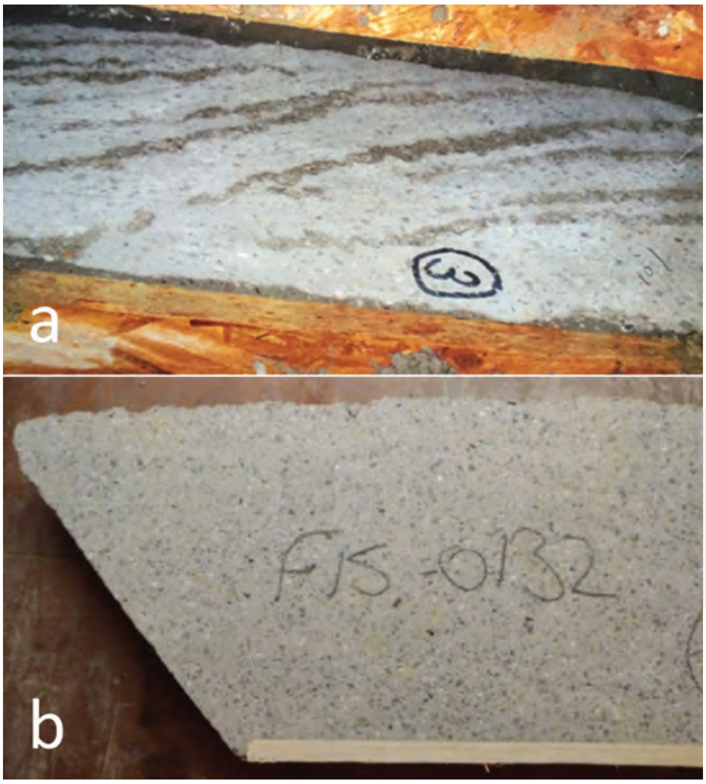

Figure 43: (a) wet mix sprayed concrete produced through standard sprayed concrete pumps with pulsation; and, (b) latest technology sprayed concrete pumps with minimal pulsation (RISPIN, MYRDAL, KLEVEN & DIMMOCK 2017)

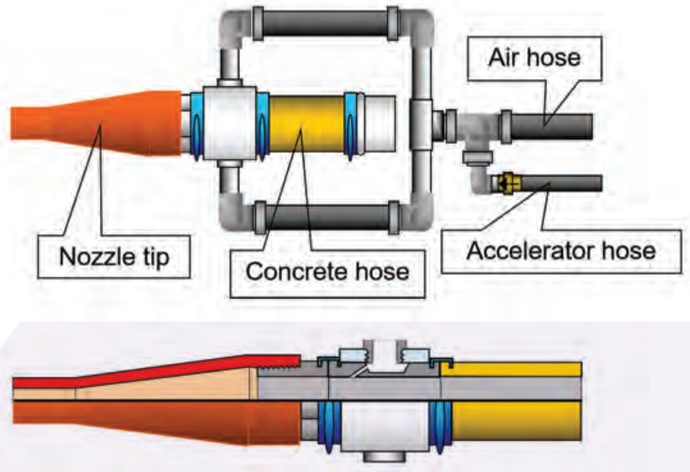

Figure 44: Nozzle set-up and air & Accelerator supply

6.5. NOZZLE DESIGN IS THE CORE OF WET MIX SPRAYED CONCRETE APPLICATION

The nozzle system is an important part of the spraying equipment. Nozzles essentially contribute to providing:

- Lower rebound
- Improved bonding
- Improved compaction through:

Proper mixing of accelerators / activators and air from a safety point of view, it is important that wet-mix spraying hoses and couplings are of the highest quality. They should be high pressure tested and certified and should not be compromised with wrong component or under rated pressure couplings and lines.

Best practice in nozzle design is to ensure a thorough and efficient mixing of the compressed air and the liquid set accelerator entering the turbo section before the nozzle as shown in Figure 44. The nozzle tip shall be designed to a concentrated focused flow and not spreading too much. Worn nozzles must always be replaced as the negatively impact concrete quality by improper compaction.

Operator training and standards for sprayed concrete have interested me since I started my career with sprayed concrete in 1976. Since then I have been very active and dedicated much time to raise the understanding of sprayed concrete and worked on national and international specifications, best practice guidelines and nozzleman training programs. I have been involved in EFNARC from 1990 to 2016 including four years as President. I have also been a member of EN workgroup for the new sprayed concrete standard EN 14487-1 and EN 934-5 and one of the founding members of ITAtech in 2011.

30-40 years ago, sprayed concrete was seen as dirty and unattractive work and with no qualification requirements. This is unfortunately still the case in many markets worldwide.

Sprayed concrete is a crucial part of rock support and safety. The nozzleman or operator is one of the most important links in the chain to produce safe, high quality, durable and environmentally friendly sprayed concrete. The final impact on quality and performance lays in the hand of the operator. The best mix -design and the best equipment does not help if spraying is not done properly. (Refer Figure 45) Spraying is a complex process. Qualifications and understanding of the principles of sprayed concrete and rock support is needed to maximise quality and minimise rebound. The final result depends on correct angle, distance, accelerator dosage and movement of the robot- arm amongst other factors.

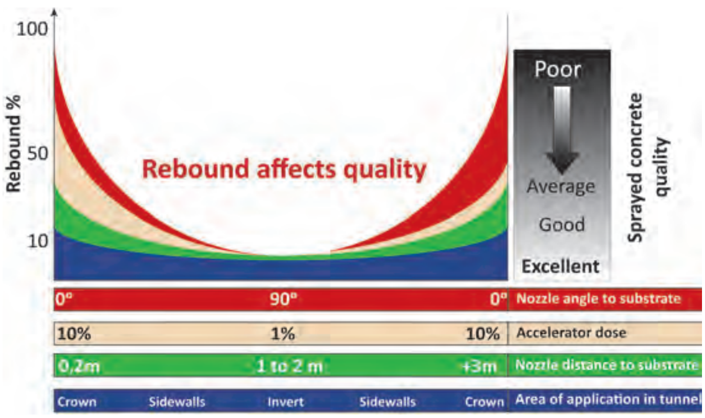

Figure 45: Spraying factors that influence quality and rebound

Bringing wet mix concrete into the tunnel is expensive. Therefore, it is crucial that the work is done by qualified operators. Globally there are no standards or requirements for a certification to be a sprayed concrete operator. This differs from all other types of work in the construction industry as an electrician, steel fixer, plumber, welder or machine operator. Hence projects can take employ any person from the population to do the sprayed concrete work! This is still practiced in many projects around the world, where the understanding and acceptance of sprayed concrete remains low. Thankfully, the trend is heading in the right direction, as good guideline is in place in countries where sprayed concrete has got acceptance and good specifications. These countries include for example United Kingdom, Sweden, Norway, Hong Kong, Australia, Norway, Austria, Switzerland, France, and also many major projects worldwide. These countries and projects have requirements that only experienced and certified operators can do the spraying work. Typically, they have established local certification courses and test the operators need to go through and pass. Normally tests include both theoretical (understanding basic principles of mix design and how sprayed concrete works and should be applied) and practical part (spraying). The certification process has both improved the quality of sprayed concrete and reduced the overall cost. The cost reduction is due to lower rebound, higher production and less failure requiring re-spraying. In these projects the sprayed concrete operators have both high status and high compensation. This helps also recruitment – creating a positive cycle.

The need for an internationally authorized cross-border Nozzleman certification scheme in robotic wet sprayed concrete process is urgent. The large construction projects, globally operating tunnelling and mining contractors and big mining companies increase the quality requirements of the spayed concrete. Lining structures are growing both in tunnelling and mining industry while the use of sprayed concrete in underground works is growing all the time.

The EFNARC Nozzleman Certification Scheme has been developed to answer that need. The Scheme is flexible as it operates through Examiners that can travel and assess experienced Nozzlemen for their theoretical and practical skills at their workplace wherever they are. Quality is ensured by certificate revalidation after every 3 years. The first course and certification were done in 2009 in Hagerbach test gallery in Switzerland. The EFNARC scheme is now endorsed by the ITA.

The course lasts two and half days including both theoretical and practical part with exam on both. The exams need to be passed to get the certification.

The certification should be mandatory in all projects globally and part of any local standard. I strongly recommend using the EFNARC scheme as it is purpose made for robotic wet sprayed concrete for rock support by the global leading worldwide sprayed concrete experts.

For more info see website: www.EFNARC.org

ITA/ITAtech and ITACet should play an active role in training and certification. They should also work with the member nations, local bodies and customers to promote nozzleman training and certification and make sure the regulation and practice are in place.

7.1. COMPUTER SIMULATION THE FUTURE TRAINING TOOL

Virtual reality computer simulations are more than tools to speed up learning process and save money. They are all about effectiveness. Having more highly skilled employees is what the future is all about.

7 >> The rise of the nozzleman

Sprayed concrete simulators are currently offered by several of the global suppliers of sprayed concrete equipment and construction chemicals. The simulator is an efficient tool to learn and practice the spraying operation of the control units and to do virtually spraying. (Refer Figure 46) There is no risk of machine damage from errors or no material consumption nor accident. The training environment is environmentally friendly and stress-free enabling quick learning and understanding of the principle of sprayed concrete. The simulator is a good way to test if somebody new is at all capable of learning to become a qualified operator before he/she is put into real work. This saves time and money.

For experienced operators it is beneficial to put them through simulator training and test to see their abilities and areas for improvement. The modern simulators work with real machine control systems from the spraying machine and virtual 3D tunnel profile. The simulator measures the thickness, rebound, drop out, accelerator dosage, concrete capacity etc. After spraying you get a report of the work. The simulator is the best way to attract young people to become interested in being a sprayed concrete operator. At Normet, we have completed over 500 simulator trainings with people over a couple of years. The results show that we on average could improve operator efficiency of the applied concrete by over 23 % (less rebound, less drop out, less accelerator consumption and higher capacity) – quite an achievement!

Simulator training should be obligatory as part of the operator training and test/certification. There should be a requirement for minimum hours in the simulator and with passed test before the certification and real spraying, and in the UK they have built this into enabling operators to move faster towards EFNARC training and accreditation. Every operator, new and old, should go through simulator training once a year to be checked of their capabilities and competence.

Figure 46: Normet concrete spraying simulator – Top: the "cave", or Bottom: Virtual Reality Headset approach

8 >> Future development

The computer-controlled systems on the spraying robots has enabled machine producers to further develop and offer mine owners real time monitoring of their sprayed concrete operations. However, recently the trend in tunnelling projects that have a focus on daily control, is that the machine data analysis is now done either by USB download from the machine or, in more advanced projects, via real-time data transfer by wireless local area networks in the mine or tunnel project. As with all monitoring systems, the value comes from processing the data to enable informed decision making to improve the sprayed concrete process underground. Availability of as-built data and process information are crucial as the industry increasingly adopts Building Information Modelling (BIM). There is demand in the future for different machines to communicate and share data among each other in order to improve efficiency and avoid doing the same operations and measurements several times. Information exchange gives tremendous time and economical savings. The drill jumbo makes the scanning, provides information about the rock conditions ahead, water, other weak zone etc that require special precautions for support. The data is shared with the charging machine and spraying robot. This will save the scanning operation before spraying, as the profile has already been scanned by the drilling jumbo. The systems are in place today, but the different suppliers need to agree to cooperate and build open source systems that can communicate with each other.

8.1. SCANNING

To improve safety, and to fulfil the requirements of the sprayed concrete lining specifications, scanners are introduced to the sprayed concrete equipment to monitor and control applied thickness. Current capabilities include the ability to measure and monitor sprayed concrete thicknesses real time and transfer data to site office teams via wireless LAN networks as indicated in Figure 48. This is area is still being developed. Accuracy, simplicity in use and, last but not least, the time taken for scanning sprayed concrete and excavation profiles will be significantly improved in the near future, with plots being available underground within minutes, as per the example output illustrated. The goal is that the scanning should only take less than 5 min per scan.

Normet is working to enhance software and measurement systems capabilities to provide automated spraying equipment that can even spray to exact specified design profile as indicated in Figure 47. This would be very valuable for single shell lining construction.

The spraying robots can be fully automated in the future. Scanning data is critical in automation. Automation will promote and increase the use of Single Shell lining with sprayed concrete. In next 5 years we will, in my view see projects where spraying operations and the concrete logistics are carried out remotely without people at the face. The sprayers and trans mixers are self-driving and controlled remotely from above ground. The new scanning technology and fully automatic spraying make this possible. Remote controlled driving is already well developed and in use in mining operations for hauling and loading. This will be the new and improved way to make the tunnelling and underground work both safer, better work environments and more attractive for young people. Self-driving equipment can as well operate more accurately in narrow tunnelling without any damage or collision risk and this give better utilization and reduced cycle time. Hence, tunnels can be built faster. In our industry the big cost driver is time – **Time is Money**

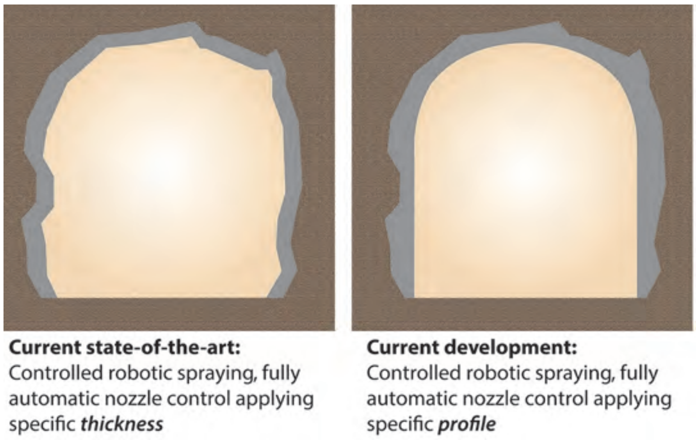

Figure 47: In the future automated spraying equipment can spray the exact specified designed profile

Figure 48: Future excavation and sprayed concrete scanning development, illustrating interfaces between nozzleman's real-time remote-control display and wireless LAN data transfer between spraying machine and outputs being sent to office for analysis and QC record (Normet)

8.2. BATTERY DRIVEN SPRAYER

Equipment plays a critical role in reducing CO_2 emissions in tunnelling and mining, and battery-driven processes are critical to meet this objective. Lately, many leading global suppliers have introduced battery powered equipment for different underground processes – drill jumbos, loaders, utility vehicles etc with the first of Normet's battery-powered charging machine was demonstrated in June 2019. At Bauma 2019 Normet launched a fully battery-driven portfolio and show cased a battery driven sprayer Spraymec 8100 VC Smartdrive. It has all the same features as diesel-powered Spraymec 8100 VC, only the diesel powerline is replaced with a battery as shown in Figure 49. The machine can be equipped with the latest scanning system, SmartScan, and assisted spraying technology, SmartSpray. Several machines are already heading for major tunnelling projects.
Battery powered equipment purchase price is higher than traditional diesel engine powered equipment due to the high battery cost. Battery technology is developing rapidly, driving the battery cost down. The business case is attractive already today. Productivity is increased, as battery-driven equipment moves faster uphill than diesel-powered. Additionally, savings in diesel, maintenance, cost of engine and driveline and saving in ventilation cost mean that the payback time for additional investment is short.

Figure 49: Normet EV SC 8100 – fully battery powered and electric spraying

8.3. SPRAYED CONCRETE WITHOUT CEMENT IN THE FUTURE - GEOPOLYMER

Portland cement has a quite a many challenge
- CO_2 emission during manufacturing
- mechanical properties (e.g. low tensile strength, porosity)
- durability (e.g. lack of fire resistance and chemical resistance).

Some of these issues might be solved if a geopolymer binder replaces Portland cement in sprayed concrete. Geopolymers are cementitious materials with three dimensional structures that are formed by chemical activation of Sodium silicate + Low Calcium Fly Ash + Blast furnace slag. Several wastes or by-products, including coal combustion ashes, metallurgical slags, construction and demolition wastes can be utilized for the production of geopolymer concrete and construction components.

Geopolymer has following advantages vs OPC based concrete:
- Eco friendly – 80% CO_2 reduction compared to OPC concrete
- Calcium free
- No shrinkage or cracking
- High chemical and fire-resistant (no additional fire protection needed, no spalling
- Good workability

However, 'pure' geopolymers need thermal curing to gain acceptable early age strength. Therefore, geopolymer concrete has typically found its application within the precast industry. To widen the applicability of geopolymer concrete, the engineering properties, particularly in terms of setting time and strength gain at ambient temperatures, need to be improved. An attempt to develop a setting and hardening accelerator for geopolymer concrete cured at room temperature started three years ago in Normet Construction Chemicals R&D (Myrdal & Griffith 2014). Table 6 shows a fly ash-based geopolymer mortar mix design, and Table 7 shows the strength development of this mortar with and without an accelerating admixture at high dosage (10% by weight of fly ash). The early age strength can be exceptionally high, even when cured at ambient temperature. Preliminary tests, not yet published, have shown that these accelerated mortars are very resistant to fire attack (1,000°C) -Refer Figure 50 - and acidic attack (10% sulphuric acid).

CONSTITUENT	AMOUNT (g)
Standard sand (EM 196-1)	1,350
Low-calcium fly ash (type F)	450
Sodium silicate, SiO_2/Na_2O molar ratio 3.25, 38% solution	126
Sodium hydroxide, 45% solution, 16.6M NaOH	54
Water	25
Superplasticiser, TamCem 11, 42% solution	2
Accelerator, 10% by weight of fly ash	45

Table 6 Geopolymer mortar mix design (Myrdal & Griffith 2014)

NON-ACCELERATED MORTAR (MPA)	ACCELERATED MORTAR (MPA)
1 hr	2.0 ± 0.2
3 hrs	5.1 ± 0.3
24 hrs	8.8 ± 0.3

Table 7: Compressive strength of geopolymer mortar cured at 20°C (MYRDAL & GRIFFITH 2014)

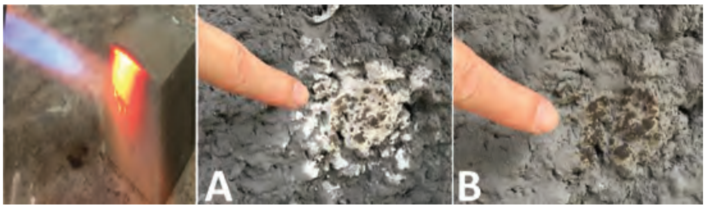

Figure 50: Effect of propane torch on a 4-5 hours old fly ash grout after 1 min fire exposure (1300°C)

A: Immediately after heat exposure (white hot/glowing)
B: After cooled down to ambient temperature (dark spots)

Is this the future of sprayed concrete materials? Is this the answer to reduce CO_2 footprint and look for more durable solution? I believe this will be a good solution for the world. The industry must be ready and willing to test in order to develop a user-friendly system that meets all the application requirements. Somebody need to be the first to use it in a project. Solution for sprayed concrete with accelerated Geopolymers are ready, full scale testing needs to begin. Geopolymers are already successfully used in tunnelling for backfill grout behind TBM segment.

8.4. TUNNEL DESIGN PROGRESSION

With an ever increasing focus on further efficiencies and the need to reduce carbon footprints, project teams are increasingly developing designs based on the use of permanent sprayed concrete rock support as modern mix design and modern application processes, coupled with the extensive durability research on existing wet-mix sprayed concrete linings from projects in Scandinavia and the UK for example, have shown there are opportunities to design more efficiencies, particularly with tunnel lining thickness.
As shown in Figure 51, a number of technical developments have led to design improvements for sprayed concrete linings, these include:

- An overall improvement in the quality and durability of the sprayed concrete material
- Enhanced concrete durability by replacing conventional steel mesh reinforcement with high performance structural fibres, be they steel or structural polymer varieties
- The use of tunnel scanning technology to ensure the spraying to the correct thickness and tunnel profile leading to the removal of lattice girders and arches
- The development and use of spray applied waterproofing membranes, allowing secondary linings to be sprayed, rather than cast, leading to potentially more slender secondary linings
- Improved materials knowledge leading to more perceptive design solutions, maximizing the bond and beneficial behaviours between layers that make up the lining
- For some structures like metro stations, the use of permanent sprayed concrete has allowed the architects to be more creative with the geometry of tunnels and junctions, and improved "flowable" ergonomic designs that support the mass movement of the travelling public in underground transport systems, resulting in economical design solutions

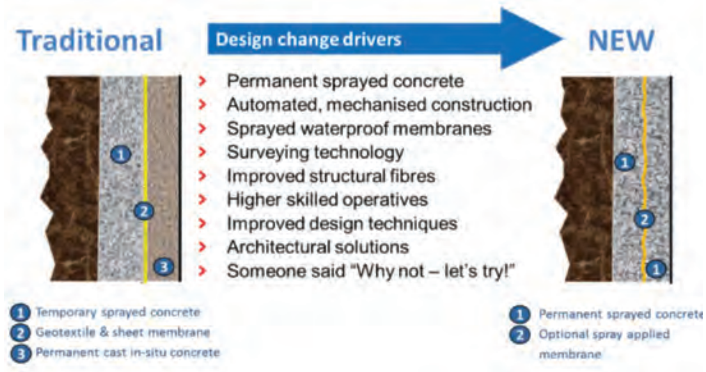

Figure 51: Design drivers for thinner sprayed concrete linings

Current thinking for sprayed concrete linings in combination with spray applied waterproof membranes is to simplify the design philosophy and consider all the ground and water loads are acting on a permanent primary sprayed concrete lining and consider "Single shell linings" (Thomas and Dimmock 2017). Whilst the single shell of sprayed concrete will cater for all the ground loads, the water loads must also be addressed.

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This can be achieved using a spray applied waterproof membrane where the adhesive strength of the spray membrane will resist the typical ground water pressures for most shallow (less than 40m deep) tunnels. Inside the spray membrane layer can be a relatively then final coat of sprayed concrete as a protection to the spray membrane and can accommodate fixings for tunnel furniture and also, if needed, act as a passive fire protection layer as indicated in Figure 52.

Modifying sprayed concrete with polymers has a lot of potential. The modified concrete can be waterproof and form a more flexible, crack resistant lining in a single shell design approach. This could be augmented with a sprayable waterproofing final coat that would substantially speed up and reduce costs of major tunnel works adopting sprayed concrete.

Regardless of design philosophy or approach, the reduction in

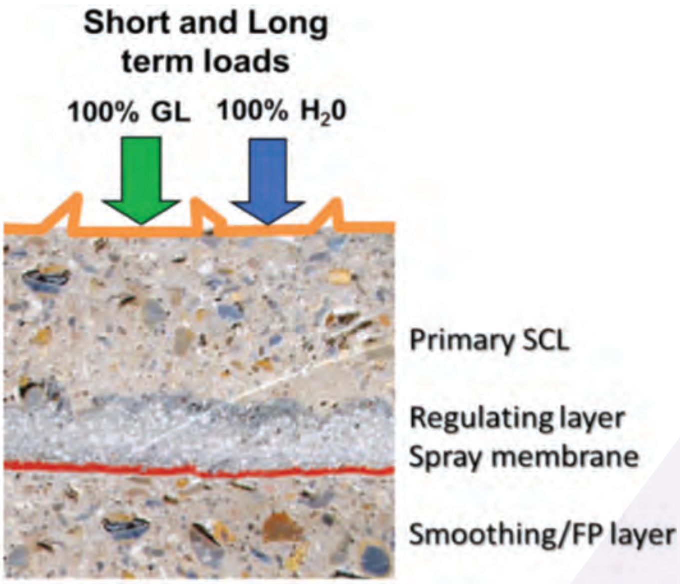
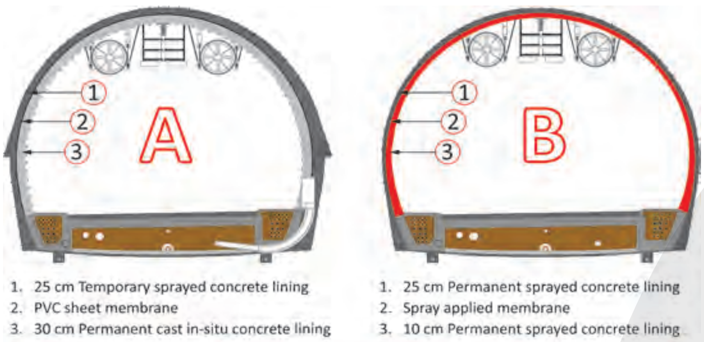


Figure 52: New design concept for Sprayed Concrete Linings (SCL), (FP = Fire protection)

the lining thickness with modern load sharing design approaches, reduces significantly the amount of concrete and therefore cement used in tunnel construction. As can be seen in the 1km long twin lane road tunnel example in Figure 53, significant CO_2 savings are possible, let alone reductions in excavated material for landfill, and the reduced impact on the local environment from small diameter tunnels.



Option	Spoil	Option	CO_2
A - Traditional	97,818 m³	19,278 m³	10,983 t
B - New design	90,932 m³	12,382 m³	8,504 t
SAVING	**7%**	**36%**	**23%**

Figure 53: 1km twin lane road tunnel illustrating environmental savings between traditional double shell linings, and new load sharing linings with spray membranes

9 >> Conclusions

- This is a paper for the new young entrants to the wonderful sprayed concrete world, but also for the old hats amongst us, as a reminder of checking and getting the sprayed concrete basics right, and to re-focus our thoughts to develop and maximise this technology!
- Sprayed concrete is concrete – let's increase its use as a robust and flexible building material
- We need to innovate again. Not much has happened since the 1990s. We seem to be only driving incremental efficiencies without any step change in innovation
- The industry needs to up-skill people with training and certification to enhance the credibility of the process by ensuring high quality end results
- Why me? Whether a client, designer or contractor, there is often reluctance to take risk and be first to try new things. Contracts should address incentives for innovative solutions that give improved quality and total cost saving over the life of the structure
- There is a lack of understanding of applied costs and what's important to focus on to drive real savings
- Some green development shoots – Electric vehicle drive, thinner tunnel linings using new material technologies, resulting in substantial CO_2 reduction and safety enhancement to match current legislation needs

During the last few years wet-mix sprayed concrete is now globally accepted has become the standard rock support method for almost all tunnel projects as temporary support, but has also been introduced and grown in popularity in the mining industry. It is a large and complex business, on the one hand imposing high safety standards to protect the miners and on the other hand requiring high productivity and output to recover the costs of extracting minerals and ores from far beneath the surface.

Mining puts many difficult demands on sprayed concrete and its application, such as logistics and temperature constraints which with the use of modern admixture and equipment technologies can be overcome.

Sprayed concrete as a building method would have a much larger field of application. However, until today the degree of utilization is unfortunately still rather limited. One of the advantages of sprayed concrete is its flexibility and speed of application. Concrete which can be placed simply with a hose against form work, rock or concrete surfaces, may architecturally and constructively be varied. The only limit is the imagination and the desire for experimentation.

We therefore call upon all contractors, architects, authorities and consultants:

Concrete technology, know-how, equipment and materials exist and may be mobilised to increase the range of our building activities as soon as someone plucks up courage to utilize the building method of the future: Sprayed concrete is concrete!

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