MODERN COMPOSITE SPRAYED CONCRETE WATERPROOF TUNNEL LININGS USING SPRAY APPLIED WATERPROOFING MEMBRANE; DESIGN, SYSTEM LAYOUT, TECHNICAL PROPERTIES AND RECENT EXPERIENCES

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ABSTRACT: This paper describes an innovative system for providing ground support and waterproofing for underground structures. The system consists of a composite single-shell structure based on fibre reinforced sprayed concrete with an integrated sprayable waterproofing membrane. The membrane is embedded in a sandwich structure with significant tensile and bonding strengths on both sides, hence giving the system a mechanically continuous character and unique waterproofing features.

The detailed layout of the system, its technical properties and possible areas of cost-effective use are presented.

Furthermore two different completed projects are reported; the recently constructed Viret Tunnel as part of the Lausanne Metro M2 in Switzerland and the rehabilitation of the concrete lined Chekka Road Tunnel in Lebanon.

In these case studies the composite sprayed concrete waterproof lining with spray applied membrane was applied as the functional waterproofing and support of the tunnel. The design of the tunnel linings comprise both drained and undrained structures. Experiences with design, construction and cost-effectiveness are compared and discussed.

BACKGROUND

Waterproofing of underground structures with a spray-applied, polymer based membrane in combination with sprayed concrete has been developed and established as a method over the last ca 10 years.

The main idea behind this method is to integrate the waterproofing in a permanent sprayed concrete lining. In this way a relatively thin and waterproof structure is established which is compatible with a permanent lining based sprayed concrete and rock bolts.

This method can be a cost-effective alternative to the traditional waterproofing methods in a number of situations, in which the traditional systems face particular difficulties or limitations.

A number of successful projects under quite different conditions and design requirements have been completed over the last few years with this system, demonstrating the cost-effectiveness and technical versatility.

The specific method and technical details which are reported in this paper refers to the waterproofing system Masterseal®345 which has been developed by BASF Construction Chemicals.
SYSTEM LAYOUT AND TECHNICAL PROPERTIES

This technical solution for waterproofing consists of an impermeable spray-applied membrane which is embedded between within a sprayed concrete structure. The membrane bonds to the sprayed concrete on both sides with a significant tensile bonding strength. It is essential to understand this technical solution as a composite system, in which both sprayed concrete and the membrane constitute vital functional parts.

The membrane itself needs a minimum thickness of 2 mm in order to be watertight. Additionally the tensile bonding strength on either side of the membrane is significant. Normally >1 MPa tensile bonding strength is achieved. On a smooth cast-in-place concrete surface > 2MPa is achieved with correct application.

This bonding property makes the interface between membrane and concrete impermeable. Hence, no migration of water along the membrane concrete interfaces can occur. This is very important system property.

This property makes a bonded spray-applied membrane fundamentally different from other waterproofing systems like sheet membrane systems with drainage geotextile or drainage shield systems with PE foam sheets or light concrete pre-cast elements.

These system features lead to the following important technical properties of the sprayed concrete – membrane composite liner:
- An eventual hole or imperfection in the membrane does not necessarily lead to a seepage point, since this imperfection must coincide with a seepage point in the concrete.
- An eventual seepage point through the membrane can be resolved locally exactly where the seepage occurs, since this point corresponds to the seepage channel in the concrete behind the membrane
- The membrane-concrete composite liner is a mechanically continuous structure and shows a monolithic behaviour. Hence, the entire thickness of this structure can be considered part of the final lining. This is visualized in figure 1 below.

Figure 1. Spray applied waterproofing membrane Masterseal®345 in a continuous composite structure with sprayed concrete. The photo to the right shows a uniaxial compressive failure situation which demonstrates the crack bridging and monolithic properties of this system.
**Durability considerations**

Long term durability of a composite liner is more than the chemical durability of the membrane material. Based on a spray-applied membrane and sprayed concrete involves an understanding of which failure mechanisms which can potentially occur. An intact and complete sandwich structure is essential to avoid mechanisms which can lead to failure over time.

Such mechanisms could be delamination of the membrane from the substrate or external mechanical damage. Figure 2 below shows how the composite structure maintains long term durability.

**Figure 2.** System properties for composite sprayed concrete liner with spray applied waterproofing membrane. Tensile bonding strength and monolithic mechanical behaviour are key properties of this technical solution.

A. The membrane is exposed to water through a joint or channel through the substrate rock or concrete. The water cannot migrate along the membrane-concrete interface, nor propagate through the actual membrane material. The membrane is only exposed to water in points or thin lines where the seepage feature intersects the membrane,

B. Potential situation with delamination without sprayed concrete on the inside of the membrane. The water pressure results in tensile stresses at the membrane-substrate interface. A propagating delamination mechanism can occur.

C. Complete composite structure with sprayed concrete on both sides of the membrane. The mechanically continuous structure prevents any propagating delamination mechanism.

**DESIGN ISSUES**

**Basic principles**

Composite liner with spray-applied waterproofing membrane and sprayed concrete can basically be designed in two main categories of structures:

- **Globally drained tunnel structure**, in which only a part of the tunnel profile is waterproofed (like the walls and crown) Water can seep into the tunnel (e.g. through the invert, lower part of walls, or through systematically installed drainage stripes) hence, avoid a global static groundwater pressure build-up.

- **Globally undrained tunnel structure**, in which the waterproofing system covers the entire tunnel perimeter, including the invert. No water can seep into the tunnel. Over time the structure will be exposed to full static groundwater pressure.

These two main categories of design layout are shown in figures 3 and 4 below. When designing a globally drained tunnel structure it is necessary to make a consideration of the drainage effect of
the jointing of the rock mass. Extra drainage stripes installed on the substrate can be necessary to achieve the necessary drainage effect.

Figure 3. Principal sketch showing an example of a globally drained waterproofing situation (vertical section). The ground water is allowed to seep into the tunnel (in reasonably small amounts) through the walls and the invert. Hence, the rock mass will be drained around the tunnel, and a build-up of water pressure is avoided. Design example realized at Nordöytunnelin, Faroe Islands (Lamhauge et al, 2007)

Figure 4. Principal sketch (vertical section) showing the waterproofing of a tunnel as a globally undrained structure. The waterproofing encompasses the entire tunnel perimeter. The inner concrete lining needs to be designed for the full static groundwater pressure.
Detailed design issues – substrate roughness

Since this method is based on a mechanically continuous structure including the substrate concrete, the bonding properties are of particular importance. The performance of the system depends highly on the quality of the substrate. Therefore the substrate properties need to be specified. Two issues need to be particularly addressed:

- Distinct surface irregularities (sharp edges, holes, rock anchor plates, steel arches) need to be smoothened out in order to facilitate the application of a continuous membrane.
- The detailed roughness of the sprayed concrete surface has to be of a favourable order. This means that the aggregate grain size should be kept at a maximum of 8 mm. 4 mm maximum grain size provides an even better surface

These are issues which should be included in the design from the beginning and implemented from the start-up of the works at the latest. In this way one can optimize the works in order to provide for a successful establishment of the waterproofing.

Detailed design issues - wet spot management

The curing of the membrane takes place with a combination of evaporation of water and hydration of cement. For this reason the membrane cannot be applied directly on water seepages. The membrane needs to be protected from direct water influence during the curing. First after a certain level of curing, the waterproofing and mechanical properties of the membrane are in place.

Water seepages therefore need to be drained (permanently or temporarily) before the membrane can be applied. There are several ways to solve this in a practical and simple manner.

This acknowledgement implies that there is a certain limit as to how wet conditions, in which this system can be applied cost-effectively. A situation with very dense seepages will require extensive (and costly) drainage works, whereas a tunnel with few and minor seepage points will require only a limited amount of wet-spot treatment prior to the application of the membrane.

Detailed design issues - freezing

The membrane does not have any frost insulating effect. The frost-insulation properties of the composite liner system depend on the thickness of the inner lining of concrete. When freezing can be expected, one needs to establish the design freezing parameter $F_{100}$ in h °C, the maximum number of hours of temperature below 0 °C in a 100 year period. With an inner lining thickness of 5 cm sprayed concrete, this composite liner can resist up to 5000 h °C.

Detailed design issues - fire safety

Masterseal® 345 does not contain any inflammable components. In the event of a fire it is self-extinguishing. When exposed to higher temperatures, the membrane melts and carbondioxide and water (vapor) is emitted.
An area in a tunnel which has been damaged by fire can be refurbished by removing only locally the damaged concrete lining and remains of waterproofing. New composite liner can subsequently be established locally where the damaged has occurred.

**APPLICATION OF THE SYSTEM**

**General**

The successful application of the composite liner with sprayed concrete and spray-applied membrane includes the employment of state-of-the-art sprayed concrete technology in order to obtain excellent technical performance and long term durable rock support.

The working sequence in establishing the system is:

a. establishing primary rock support with fibre reinforced sprayed concrete, surface properties suitable for subsequent spray-application of membrane
b. removal/drainage of wet-spots
c. application of the membrane, allow for curing
d. application of inner layer of sprayed concrete to designed thickness

In the following the application of the membrane is particularly addressed.

**Improvement of the substrate prior to application of the membrane**

The substrate cannot be too rough or irregular. If the substrate is too rough and irregular, a smoothening layer of sprayed concrete must be applied. Details are shown in figure 5 below.

Formwork surfaces need to be high pressure washed (1400 bars) so that formwork oil, deteriorated concrete, dust, and soot is removed. Sprayed concrete surfaces need to be high pressure washed if older than 4 months (during construction). Otherwise washing with air and water from the sprayed concrete machine is sufficient.

Fibre reinforcement in the substrate sprayed concrete does not (as one might tend to think) penetrate the membrane. However, during the application of membrane it is essential to spray on the “wet” side on order to cover the fibres completely. This requires attention from the spray operator regarding this particular issue.
Figure 5. Suitability of different substrate surfaces for spray applied waterproofing membrane.
A: Maximum aggregate grain size > 8 mm: the substrate is too rough, not suitable
B: Maximum aggregate grain size = 4 mm: the substrate is very smooth, suitable
C: Maximum aggregate grain size = 8 mm: the substrate is sufficiently smooth, suitable
D: Thin and non-continuous sprayed concrete: this substrate is not suitable

Handling of wet spots

The most reliable and simplest method to drain spot seepages is to drill small drainage holes (e.g. 10 mm diameter and 30-40 cm length) which are fitted with small injection packers. These injection packers are left open and fitted with a protective hose. Then the membrane can be applied. In this way an active drainage is kept functional during the application of the membrane and the following curing of the membrane. When the membrane is completely cured, the packers are injected with an amount sufficient to fill the hole. This method is shown in figure 6 below.

The photo to the right in figure 6 shows a situation with dense point seepages through the substrate in which this method of temporary drainage has been successfully applied.

When large point seepages occur, it is recommended to install drainage channels and drain to invert permanently.

Application of the waterproofing membrane

The waterproofing membrane (Masterseal® 345) is delivered as a powder product which consists of an ethylene-vinylacetat-copolymer component and a cementitious component. During the application the product is mixed with water, creating a pasty substance.
Figure 6. Example of temporary drainage of minor seepage points through the substrate prior to application of the waterproofing membrane. (Holter, Tappy, 2008)

1. Drilling of drainage hole, diameter 10mm, length 30-40 cm, insertion of injection packer
2. Spray application of waterproofing membrane
3. Injection of packer after curing of membrane

The application process employs the dry spraying method, in which the mixing of water to the product takes place in the nozzle. This mixture is sprayed onto the substrate with an average thickness 3 mm, as even as possible. A minimum of 2 mm membrane thickness is required for watertightness. The essential detail during spraying is the precise and consistent application of ca 3 mm thickness. This requires a low and controllable material output, and carefully fine-tuned parameters like nozzle distance and speed of the nozzle over the surface

When the mixture cures (evaporation of water and hydration of cement) a continuous polymer chain structure is formed. When the curing is complete, this polymer chain structure is watertight.

The application can be done manually with hand held nozzle off a working platform or mechanized with a spraying robot.

These two working modes are shown in figure 7 below. For larger projects there are many advantages of spraying mechanized. Mechanized application gives far larger capacities, as well as a far more consistent application of the desired thickness. Quality control of the application is also simpler and more reliable, since one gets a precise registration of the sprayed area and the material consumption in this area.

**Application of the sprayed concrete inner lining**

The inner lining is applied with wet-mix sprayed concrete with fibre reinforcement. (shown in figure 8 below) Either type, steel or structural polypropylene fibres can be used.

The minimum thickness of the inner sprayed concrete lining is 4 cm for cases in which there is no expected ground water pressure. In cases with expected water pressure, the inner sprayed concrete lining, including details in the invert, needs to be designed for this.
The timing of the application of the inner sprayed concrete lining is important. The membrane needs to reach a minimum level of curing before application of the inner concrete can take place. The speed of the curing is dependent on temperature and humidity.

Figure 7. Left: Application of sprayable waterproofing membrane Masterseal®345 manually from working platform. (water seepages are drained to invert with drainage channels) Right: mechanized and computerized application of the membrane with MEYCO® ROBOJET LOGICA.

Figure 8. Application of sprayed concrete inner lining onto cured waterproofing membrane. Left: spraying of concrete with normal sprayed concrete machine. Right: spraying of concrete with precise thickness with computerized and mechanized spraying robot MEYCO® ROBOJET LOGICA.

The achieved curing status is measured indirectly by measuring the hardness of the membrane using a Shore A hardness measuring device. Under favourable conditions, sufficient curing for the application of the inner sprayed concrete lining can be achieved after approximately three days.

EXPERIENCES FROM THE CONSTRUCTION OF THE VIRET TUNNEL, LAUSANNE MÉTRO M2, SWITZERLAND
The project

The Viret tunnel is part of the new Metro Line 2, and passes under the historic centre of the city. The area over the tunnel is particularly sensitive with the cathedral and groundwater saturated soils. The most critical part of this tunnel (275 m length) has a very shallow location. The tunnel is located in molasse, with rock cover ranging from a 2.5 meters to 10 metres. The overlying quaternary sediments consist of water saturated sands, gravels and moraine. (figures 9 and 10 below)

Figure 9. Tunnel Viret, Lausanne Metro M2. Critical cross section (Holter, Tappy, 2008)

Figure 10. Tunnel Viret, Lausanne Metro. Longitudinal section. For detailed legend please refer to figure 9. (Holter, Tappy, 2008)
In case of flow of water in the tunnel, settlements of more than three centimetres would have appeared under the cathedral. This would obviously have been unacceptable. Thus the design of the tunnel Viret includes a waterproof lining which covers the entire tunnel perimeter, figure 11.

Figure 11. Tunnel Viret, Lausanne Metro. Cross section with final design. Spray applied waterproofing membrane indicated in dashed line around the perimeter. In the crown and walls a composite liner based on sprayed concrete and spray applied waterproofing membrane was applied. The invert was realized as a reinforced cast-in-place structure. (Holter, Tappy, 2008)

The initial design included a double sheet of polyolefin of 3 mm thickness and an inner lining with cast-in-place concrete (figure 12 upper part). Difficulties had been encountered on other projects with this system, so neither owner nor designer was completely confident with this traditional waterproofing system.

For this reason the alternative design (figure 12 lower part) with a composite sprayed concrete liner with spray applied waterproofing membrane Masterseal 345 was developed in this case. This system had previously been successfully used in an undrained situation in an emergency escape tunnel in Switzerland [Meier et al. 2005].

The great advantage of this system relates to the fact that no seepage is possible between the membrane and its support, since there is a complete bonding between the sprayed membrane and the concrete.
Figure 12. Cross sections of concrete linings, original design and revised innovative design. Upper part. Original design with polyolefin sheet membrane and inner lining with cast-in-place concrete lining. Lower part: Realized design with composite sprayed concrete liner with spray applied waterproofing membrane Masterseal 345. (Holter, Tappy, 2008)

Figure 13. Tunnel Viret, Lausanne Metro M2. Right: Situation during construction with Masterseal®345 sprayable waterproofing membrane applied in the entire tunnel perimeter, including the invert, just before the commencement of the works with the structure in the invert. Left: Finished tunnel with final sprayed concrete composite waterproof liner in the walls and crown, and reinforced cast-in-place concrete in the invert. (Holter, Tappy, 2008)
The construction of the tunnel was finished prior to schedule and with a significant cost savings. Main experienced data are given in the summary at the end of the paper.

**EXPERIENCES FROM THE REHABILITATION OF THE CHEKKA ROAD TUNNEL, LEBANON**

The Chekka tunnel is a twin tube road tunnel in northern Lebanon constructed in 1977. The two tubes are 360 and 390 m long and consist of a final lining with cast in-situ concrete without waterproofing membrane. The total thickness of the old lining was approximately 90cm. Both tubes have three lanes.

![Figure 14. The Chekka tunnel before refurbishment. (Makhlof, Holter, 2008)](image.png)

Traces of water ingress along the construction joints and structural cracks in the concrete can be observed. The two tunnel tubes had to be refurbished for several reasons. The main issue was the water ingress along construction joints and structural cracks in the concrete lining, well as structural repair since deformations leading to cracks had occurred in the portal areas.

**Technical solution**

The original design called for a completely new concrete structure to be constructed inside the existing one, without removing the existing structure. This new tunnel lining would consist of steel-reinforced cast in-situ concrete with a waterproofing sheet membrane and drainage geotextile. The total thickness of this structure would have been 25 cm. This would impose a significant reduction of the width of the tunnel, since a structural base for the concrete lining at the invert also had to be included.

The contractor was aware of several recent successful application of the spray applied double bonded waterproofing membrane, which in combination with sprayed concrete constitutes a composite waterproof sprayed concrete lining. In refurbishment situations it is possible to achieve durable high-performance linings with significantly lower thicknesses than the traditional solution by using this alternative system.

Two basically different options were available when planning a technical solution with sprayable membrane in combination with sprayed concrete: globally drained or globally undrained. Both these two design options had been realized on several recent projects and could offer cost-effective technical solutions for the Chekka Tunnel as well.
The decisive design parameters for the rehabilitation of the tunnels were the following:

- Groundwater level lower than the tunnel level, with perculating water through the ground in periods with high precipitation
- The tunnel structure should be globally drained
- The concrete existing concrete structure was mainly in good condition. Defects were located to construction joints, structural cracking in some areas, and local surface deterioration of the concrete.
- Possibility to utilize the old concrete lining as a structurally bearing lining by repairing the defects
- The desire to retain as large as possible free width of the interior of the tunnel

![Figure 15. Original design A, cross section detail. Waterproofing with sheet membrane and drainage geotextile and final lining with reinforced cast in-situ concrete with 25 cm thickness (Makhlouf, Holter, 2008)](image)

The contractor proposed an alternative technical solution with the following main elements:

- Repair of the structural cracks in the existing concrete structure with injections with a resin with high mechanical strength
- Repair of the construction joints with a tailored dilatation solution including a joint seal, sprayed waterproofing membrane and sprayed concrete
- Ultra high pressure surface cleaning of the existing concrete structure, removing all hardened dust, loose particles, soot as well as deteriorated concrete
- Application of a double bonded spray applied waterproofing membrane with minimum thickness 2mm.
- Application of the inner lining with fibre-reinforced sprayed concrete with minimum thickness 4 cm.
- Application of a suitable esthetic finish on the interior surface of the tunnel
With the alternative technical solution a significant time savings could be realized, the tunnel could be left larger than originally designed retaining all three traffic lanes, without increasing the budget. A slight reduction of the construction costs was expected.

Details of the original (A) and the alternative (B) design are shown in figures 15 and 16.

![Figure 15. Alternative design B, cross section detail. Waterproofing with double bonded spray-applied membrane and final lining with fibre reinforced sprayed concrete. Original concrete lining is repaired with structural crack injection. (Makhlouf, Holter, 2008)](image)

The waterproofing membrane adheres to the substrate as well as the inner sprayed concrete lining with a tensile bonding strength of ca 1.2 MPa. Water cannot migrate along either of the interfaces between the membrane and concrete. Hence, this waterproofing represents an undrained surface sealing. The global drainage of the structure, when required during periods of precipitation, would take place behind the construction joints as well as the invert.

The layout of the construction joints represented an important detail. Since the alternative technical solution featured double bonded vital parts of the system, a mechanically continuous structure was the result. The construction joints were exposed to a longitudinal thermal deformation (opening and closing) of approximately 5 mm over the year. The construction joints occurred every 10 linear tunnel meter. Hence, a dilatation detail needed to be included in the design to secure a long term waterproof situation at the construction joints.

This was done by covering the construction joints with a joint seal which was glued with epoxy resin to the old concrete lining on both sides of the joint. Subsequently this detail was oversprayed with the waterproofing membrane, creating a continuous membrane covering the concrete as well as the joints. In order to allow for the deformations, one had to create a discontinuity in the inner sprayed concrete lining without creating any defect in the waterproofing. This was achieved by placing a 30mm by 30mm foam strip over the center of the joint seal and adhere it to the freshly sprayed membrane. Subsequently sprayed concrete could be applied onto the joint.
Finally the discontinuity was created in a controlled manner by making a 4 mm wide slot with an angle grinder to controlled depth 4 cm along the construction joint in the entire tunnel perimeter. Figure 17 above shows an example of the dilation detail at the construction joint before application of the sprayable waterproofing membrane.

**Application of the system**

The waterproofing membrane employed on this project was the Masterseal® 345 system supplied by BASF. This is a polymer-based cementitious product which is delivered as a powder. The application takes place with the dry-mix spraying method, using a dry concrete spraying machine. Minor modifications were made to this machine in order to give a constant low output and a precise dosage of water, so that a consistent membrane thickness of 2-3 mm could be achieved.

The regularity of the surface of the concrete lining in this case allowed for a mechanized and computerized spray-application of the membrane as well as the concrete. Experiences with this application method had been gained one year earlier at the Nordøy subsea tunnel project, in which approximately 18000 m² of tunnel surface had been waterproofed (Lamhauge et al 2007). The spraying system which was selected for this project was the MEYCO® POTENZA LOGICA, supplied by Meyco Equipment in Switzerland.

The spray-application of the waterproofing membrane utilized a state-of-the-art robotic machine. This machine was originally designed for the robotic application of sprayed concrete with a very precise layer thickness. The features of this machine, in particular the scanning of the substrate and the possibility to achieve a constant speed of the spraying lance, made it suited for the robotic application of the waterproofing membrane.
Scanning of the surface takes place with a digital recording with a laser scanner of the detailed surface geometry. The scanner is located at the very front of the spraying lance. The operator defines the angles of a square area on the tunnel contour to be scanned. The scanner then records the surface with a pre-defined grid density. In this case one used a 20 cm square grid density. The file with the scanned area was then in turn used for the robotic spraying of the area.

The machine had to remain in the exact same location after the scanning had taken place until the robotic application of the membrane was completed in this area. The robotic spraying of the membrane took place in the area which was scanned immediately in advance. In the given tunnel dimensions, it was possible to spray sections of 4.2 m tunnel length in the entire tunnel contour.

The robotic part of the spraying was the movement of the lance and nozzle. Feeding of air, water and the speed of the pump had to be adjusted manually. The constant speed of movement and the constant nozzle movement and distance made it possible for any given point in the scanned area to receive the exact same amount of membrane. These machine parameters had to be defined in advance. This was done in an initial exercise in order to optimize the mechanized part of the application.

With this application method very satisfactory production data were achieved. The main construction time data are shown in table 1 below.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Result, experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of tunnels</td>
<td>360 and 390 m</td>
</tr>
<tr>
<td>Total surface area to be refurbished</td>
<td>18000 m²</td>
</tr>
<tr>
<td>Application capacity waterproofing membrane (average, maximum)</td>
<td>150 m²/h, 180 m²/h</td>
</tr>
<tr>
<td>Application capacity sprayed concrete (4cm thickness; average, maximum)</td>
<td>80 m²/h, 110 m²/h</td>
</tr>
<tr>
<td>Duration of application of waterproofing membrane</td>
<td>12 working days</td>
</tr>
<tr>
<td>Duration of application of sprayed concrete</td>
<td>22 working days</td>
</tr>
<tr>
<td>1 working day</td>
<td>10 hours shift</td>
</tr>
</tbody>
</table>

Table 1. Main experienced construction time data for the rehabilitation of the Chekka tunnel. (Makhlouf, Holter, 2008)

Figure 18. Computerized robotic application of sprayable waterproofing membrane with thickness 2-3 mm (left), and fibre reinforced sprayed concrete with precise thickness 4 cm (right). The main figures of the execution of the rehabilitation works are summarized table 1 above. (Makhlouf, Holter, 2008)
When starting spraying on each shift, one only had to fine-tune the air, amount of water (in order to achieve to correct mixture ratio) and the speed of the dry spraying pump. When the crew had gained good experience with the equipment, very satisfactory application capacities of 1500-1800 m$^2$ per shift were realized.

The resulting surface of the tunnel after the application of the sprayed concrete was a grey surface with roughness irregularities in the order of 4-6mm. Several final finish options were considered, including the spray application of a fine grained screen.

![Figure 19. Left: Tunnel surface after the application of the inner lining of fibre reinforced sprayed concrete. Right: Tunnel surface after the application of the floated mortar in the crown and tiles in the walls to obtain final finish. (Makhlouf, Holter, 2008)](image)

**MAIN EXPERIENCES**

In both these cases the use of modern sprayed concrete in combination with spray applied waterproofing membrane facilitated design solutions with a number of advantages.

The main experiences with the use of sprayed waterproofing membrane in combination with sprayed concrete with regards to technical performance, construction time and construction cost are summarized in table 2 below.

<table>
<thead>
<tr>
<th>Project</th>
<th>Construction time</th>
<th>Construction cost</th>
<th>Technical / other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lausanne Metro, Tunel de Viret (Switzerland)</td>
<td>3 months shorter compared to original design with sheet membrane</td>
<td>EUR 1500 less per linear tunnel meter</td>
<td>Shorter construction time, less technical risk for mishaps during construction, no groundwater drawdown</td>
</tr>
<tr>
<td>Chekka road tunnel rehabilitation (Lebanon)</td>
<td>6 weeks shorter construction time (out of a projected 4 month construction time with original design with sheet membrane)</td>
<td>Marginally cheaper</td>
<td>Less time interrupting highway traffic. No reduction of interior width of tunnel, all three lanes kept in use after rehabilitation</td>
</tr>
</tbody>
</table>
REFERENCES


Holter, K.G. and Tappy, O (2008) Modern composite sprayed concrete waterproof tunnel linings; technical properties, system layout and design. 5th International Conference on Wet-mix Sprayed Concrete, Lillehammer, Norway, 2008
