Shotcrete: Elements of a System – Bernard (ed)

Composite linings: Ground support and waterproofing through the use of a fully bonded membrane

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ABSTRACT: Robust waterproofing of underground structures is one of the most cost-effective ways to enhance safety and function as well as to increase the design life of new and existing structures. An efficient and economical approach to waterproofing is to integrate a waterproofing layer into ground support through the use of a fully-bonded cementitious polymer-based spray-applied membrane that bonds equally successfully to the inner and outer lining and is unaffected by the concrete placement method or reinforcement type. This solution is an alternative to the more traditional waterproofing systems in a number of situations where the traditional system faces particular difficulties or limitations. The fully bonded membrane acts as a shear connector between the two layers and, where it is possible to rely on the primary lining as a permanent solution, establishes a thinner monolithic waterproof structure. This paper will highlight design considerations and present some international case studies that will illustrate the application of this system.

1 INTRODUCTION

Efficient and cost-effective lining and waterproofing solutions are required to satisfy increasingly demanding programs and to create safer and friendlier space underground. Dry tunnels are a pre-requisite in many tunneling applications, and innovative approaches such as fully-bonded spray-applied membranes, are now proven methods worldwide. The benefits of fully-bonded membranes as a direct replacement for traditional sheet membranes within a support system will be discussed later in Section 3.1.

Additional advantages of the system are gained from the sprayed nature of the membrane such as the possibility of using sprayed concrete not only as a primary lining (often considered only as a temporary support) but also as a secondary permanent lining, instead of cast insitu concrete. This has the potential of reducing the thickness of the concrete secondary lining where typically the thickness of a final cast insitu lining is in excess of 250 mm. This figure is often driven by formwork and reinforcement placement tolerances and cover requirements and is not purely based on the design loads. If formwork and reinforcement, in the form of bars, can be eliminated, through the use of Fiber Reinforced Sprayed Concrete (FRSC), the thickness of the inner lining can be reduced.

In addition to this, where it is also possible to rely on the primary layer as a permanent solution, a thinner monolithic waterproof structure is established. Both layers of concrete, primary and secondary, can therefore be considered permanent and durable elements that can and will fulfill the structural requirements both during construction and throughout the designed life of the structure. The integration of a state-of-the-art fully bonded cementitious polymer-based spray-applied membrane into concrete linings has been developed for waterproofing and at the same time to provide a shear connection between primary and secondary layers of concrete.

Figure 1. Sample cores of a fully bonded spray applied membrane sandwiched between two sprayed concrete layers.

2 THE SYSTEM

This unique composite system consists of a first layer of sprayed concrete (temporary or permanent), a fully bonded intermediate layer of elastic cementitious polymeric spray-applied membrane, typically 3 mm thick, and a second layer of sprayed or cast-in-place concrete.

A number of tunnels, cross-passages, stations and shafts have been successfully completed worldwide with this system over the last few years, under quite different conditions and design requirements, demonstrating its cost-effectiveness and technical versatility. Some examples are reported in this paper.

3 DESIGN CONSIDERATIONS

The traditional ground support method of conventionally excavated tunnels in simplistic terms considers the primary lining as a temporary lining carrying the ground loads and the secondary lining as permanent carrying the hydrostatic loads.

Design and construction methodologies are evolving and continuously adapting to provide the best possible solution to project-specific ground and loading conditions. Over recent years it has been possible to observe the following trends:

1. The substitution of traditional sheet membranes with fully bonded spray applied membranes in situations where traditional sheet membranes are particularly tricky to apply;
2. A shift from temporary to permanent sprayed concrete primary linings;
3. A shift from reinforced cast insitu secondary linings to FRSC secondary linings, with considerable savings, both in terms of programme duration and materials.

Examples of some of the projects that have followed these trends are given later.

3.1 *Substitution of traditional sheet membranes with fully bonded spray applied membranes*

Spray applied membranes are particularly advantageous in geometrically complex areas such as in lay-by niches, cross passages (Fig. 2), turnouts and crossover caverns, where installation of conventional membranes is inherently difficult and testing is challenging.

This type of membrane can be applied to limited sections to provide isolated waterproofing, for instance in the crown of tunnels in a drained "umbrella" type configuration, or as a continuous waterproofing system (fully tanked, undrained) without discrete joints or need for waterstops and compartmentalization.

Spray applied membranes are faster and more easily installed than sheet membrane thus freeing up time and space for other activities. Typically 50–100 m²/h can be manually sprayed by 2–3 operators, whilst robotic spraying can reach up to 180 m²/h, against the standard 25 m²/h for sheet membranes. A spray applied membrane does not require surface evenness however the time needed for the substrate preparation works and the consumption of material will depend upon the substrate smoothness and quality encountered (Fig. 3).

The bond properties between the membrane and concrete lining on both sides, but particularly to the inner lining, makes the interface between membrane and concrete impermeable. Hence, no migration of water along the membrane-concrete interface can occur mitigating the risk of water ingress by eliminating potential groundwater paths. This is a very important property as it makes a bonded spray-applied membrane fundamentally different from other waterproofing systems like sheet membrane systems with drainage geotextiles (Figures 4 and 5). An eventual seepage through the membrane can be easily resolved locally precisely where the seepage occurs since this point corresponds to the seepage channel in the concrete behind the membrane. For a leak to occur in a double bonded system, water has to find a path through three failure zones. Firstly a crack in the primary lining, then a tear in the membrane followed by a second crack in the secondary lining. All of these failure zones need to occur in the same spot as water cannot migrate along the membrane-concrete interface surface.

Figure 2. Complex intersections on the Heathrow baggage tunnel.

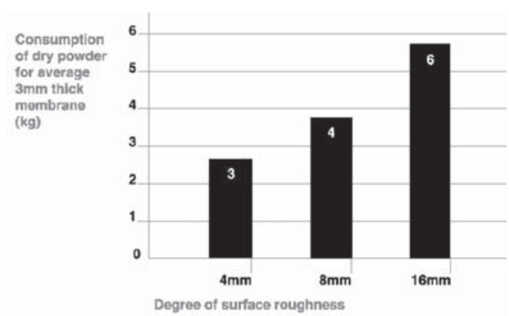

Figure 3. Consumption rates of Masterseal® 345 for various degrees of surface roughness (maximum aggregate size).

Evidence of the bond strength and crack bridging properties of the fully bonded membrane is given in sections 4.1.2 and 4.1.4.

Fully-bonded spray-applied membranes are compatible with other waterproofing systems, i.e. sheet membranes, and standard joint details between and spray applied and sheet membranes have been established, making the system totally flexible (Fig. 6).

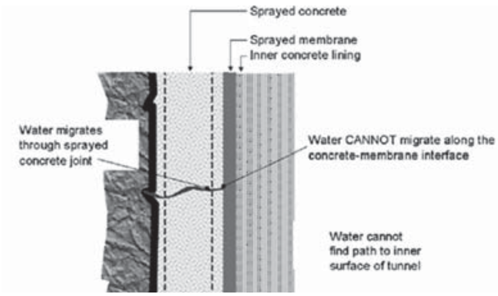

Figure 4. Fully bonded Masterseal® 345 waterproofing membrane preventing the migration of water along the concrete-membrane interface.

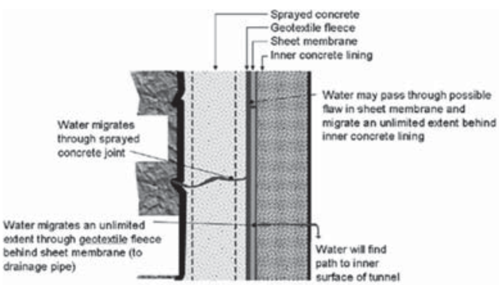

Figure 5. Water migration along the geotextile layer or between the sheet and the inner lining in a traditional support and waterproofing system.

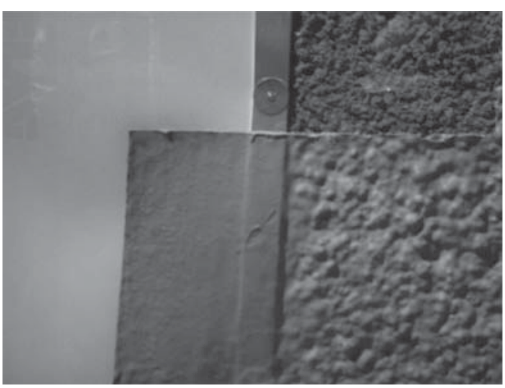

Figure 6. Interface detail between traditional type waterproofing and fully bonded spray applied membranes.

They are also compatible with:

- All concrete placement techniques, allowing placement of a sprayed inner lining which reduces the overall final lining thickness;
- Reinforcement types, mesh, reinforcement bars and fibers, on either side of the membrane, refer to section 3.3;
- Steel insertions (e.g. anchored reinforcement, drainage pipes, etc.).

The spray applied membrane is innately more robust than a sheet membrane solution, in that the creasing, folding, stretching and buoyancy effects, which are unseen but inevitable as wet concrete rises up the sidewalls of an arched tunnel profile, are avoided.

3.2 *Shift from temporary to permanent sprayed concrete primary linings*

It is important to note that sprayed concrete is only one of several methods to place concrete. The method of spraying concrete onto a surface is ideally suited for the support and construction of underground excavations. The on-going advance in material technology related to sprayed concrete, particularly with the advent of micro- and nanosilica technology, alkali-free accelerators and fiber reinforcement, has created a high level of confidence in attaining a tunnel lining with excellent durability characteristics and watertightness. In addition to materials improvement, the construction process has become highly automated thereby significantly reducing the degree of human influence that has, in the past, contributed to preventing clients from considering sprayed concrete as permanent support. Effort has also been put into the training of personnel and the creation of regulations (e.g. EFNARC nozzleman certification scheme) that have largely improved the quality of the sprayed product.

These two facets have contributed over recent years to a higher quality sprayed concrete. What once was considered an extremely porous material is now a high quality concrete with high density, low permeability and good durability. The quality of sprayed concrete linings has recently been recognized and designers have begun to rely on the primary lining as a permanent solution. Both layers of concrete, primary and secondary, can therefore be considered as durable structural elements. This is one of the key assumptions for composite behavior, refer to Section 5.

3.3 *Shift from reinforced cast insitu secondary linings to FRSC secondary linings*

Based on the successes mentioned above, permanent reinforced cast insitu concrete linings can be substituted for more economical permanent FRSC linings.

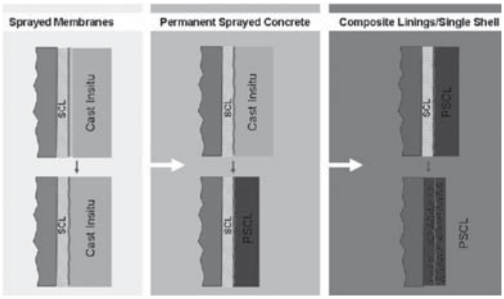

Figure 7. Trends in waterproofing and support systems (SCL = Sprayed Concrete Lining; PSCL = Permanent Sprayed Concrete Lining).

Coupled with a spray applied waterproofing membrane a permanent spray-applied inner lining is a solution which has the potential of reducing the thickness of the concrete secondary lining. Typically the thickness of a final cast insitu lining is in excess of 250 mm. This figure is often driven by formwork and reinforcement placement tolerances and cover requirements, and is not purely based on the design loads. Expensive formwork and reinforcement, in the form of bars, can be eliminated through the use of fiber reinforced sprayed concrete thereby reducing cost and time and the thickness of the inner lining.

4 THE FULLY BONDED WATERPROOF MEMBRANE

4.1 *Properties of Masterseal® 345*

Laboratory tests in accordance with international testing methods, as listed in Table 1, have been performed on the Masterseal® 345 membrane. The properties of the membrane are described in this section; the interface properties derived from the bond however, will be discussed later in Section 5.

4.1.1 *Water pressure resistance and permeability*

A tight polymer membrane is in general an excellent waterproofing barrier in its own right. The water flow is prohibited by the strong matrix of polymer chains. Water having a high surface tension is unable to penetrate into the material and pass this barrier.

Masterseal® 345 pores are 20,000 times smaller than a water drop but 700 times bigger than water molecules and therefore water is absorbed by the membrane and released as vapor. Vapor penetrates through the Masterseal® 345 membrane at the same rate as through concrete. The membrane itself should have a nominal thickness of 3 mm (localized minimum of 2 mm can be accepted and maximum of 10 mm) in order to be watertight. Above 10 mm the self-weight of the membrane may cause de-bonding during application.

The watertightness of Masterseal® 345 was successfully tested in BASF laboratories as well as at the independent test institute, EMPA (Federal Institute of Material Testing, Switzerland) and

Table 1. Properties of Masterseal® 345.

Property	Testing method	Minimum specification
Water pressure resistance and permeability	EN 12390-8: 2000 Testing hardened concrete. Depth of penetration of water under pressure	Resist up to 20 Bar to 12 months
Tensile strength at yield	ASTM D638M DIN 53504 Type S2 BS EN 180527-2	From 4 MPa (at +20°C) to 0.6 MPa when submerged
Elongation at yield	ASTM D638M DIN 53504 Type S2	80%–140% (between –20°C and +20°C)
Crack bridging	EN 14224	100% of thickness
Modulus of elasticity	N/A	Variable. See Figure 8 and 9.
Bond strength (both sides)	EN 1542 EN 1766	From 1.0 MPa to 0.5 MPa when submerged
Bulk density	N/A	585 ± 90 g/L ± 100 g/L
Water vapor diffusion	DIN 52615	Max. 300
Resistance factor		
Frost insulation	N/A	5 cm of sprayed concrete the composite lining can resist up to 5000 h °C
Fire resistance	DIN 4102	B2 or better
Rock water resistance	Resistant to Sulfates Resistant to acidic water Resistant to alkaline water	To be specified according to local geological conditions
Potable water certificate	BS 6920	Required when potable water is in direct contact to the membrane

at BMI—the Technical University of Innsbruck (Austria). Water-tightness tests performed up to 1 year, after which tests were stopped, show that the membrane has excellent resistance to water ingress and can sustain up to 20 bar pressure. It must be noted, however, that the membrane can only withstand active pressure once completely cured. Tests were performed in accordance with EN 12390-8. A layer of 3 mm of Masterseal® 345 were applied to a porous building material of the size 200 × 200 × 55 mm. Samples were stored at 20°C and 65% RH.

Six samples with Masterseal® 345 and one sample without (the reference sample) were glued in pressure vessels so that only the membrane was exposed to the water pressure. Testing was started by flooding the vessels with water and applying a constant pressure of 20 bar. After 1 hour of applied pressure 2.2 L of water flowed through the reference sample and testing was stopped immediately. In the Masterseal® 345 samples however, up to the end of the testing, 3 months and 12 months, the unexposed surfaces of all samples were dry. Three samples were removed from the vessels and split after 3 months and the remaining three samples after 12 months. The penetration depth of water into the test surface was determined on the fresh crack surface immediately after splitting. The reference sample without Masterseal® 345 showed high water inflow, as expected. The samples coated with 3 mm of Masterseal® 345 showed small and homogeneous penetration of moisture from the membrane. The penetration depths into the underlying porous building material after up to 3 months of high pressure application (20 bars) varied between 10 to 22 mm without indication of speeding up over time. In fact the depths of penetration after up to 12 months vary between 6 to 22 mm.

Apart form the observed moisture migration, Masterseal® 345 demonstrates excellent watertight performance characteristics under these adverse conditions. Water migration along the membrane/substrate contact was tested at the University of Innsbruck as the membrane bonds to the surface (following contours). This found that water migration along the membrane/substrate contact is negligible.

4.1.2 *Adhesive tensile strength, elongation and crack bridging behavior*

Various types of fracture can occur in a composite lining, depending on which part of the system breaks down under the stress of testing:

- Crack in the concrete;
- De-bonding of the sealing membrane (Masterseal® 345);
- Tensile failure of the membrane.

The adhesive tensile properties of the membrane are such that they can:

- prevent debonding of the membrane from the concrete such that there is no expansion of water between these layers and no registered increase in pressure by a manometer;
- bridge cracks and protect the inner shell from being subjected to the stress of water pressure. Masterseal® 345 is able to close and isolate cracks and minimize the surface area over which the water pressure is acting thereby keeping the force acting on the inner lining down to a minimum. This leads to the outer shell easily being able to sustain loads resulting from water pressure consequently justifying the reduction in thickness of the inner lining.

The sealing layer is therefore able not only to seal-off (waterproof) the system, but also to bridge and bond any cracks and redistribute the shearing forces effectively. The tensile strength of the membrane has been tested in accordance with ASTM D628M, DIN 53504 Type S2 and BS EN 180527-2. Results of these tests show that the tensile strength of the cured membrane ranges from 1 to 4 MPa (between −20°C and +20°C). The elongation at yield values ranged from 80% to 140% (between −20°C and +20°C). Thanks to these properties, the membrane provides crack bridging capability some hours after application. Since hardening of the membrane reduces the elasticity, the minimum crack bridging ability is achieved once fully cured. For a 3 mm thick membrane layer this ability is 3 mm. Tests were performed in accordance with EN 14224.

4.1.3 *Modulus of elasticity*

The stiffness of Masterseal® 345 is not constant, reducing with increasing elongation (Figures 8 and 9). The stiffness values are a function derived from the Tension (Fmax) and Elongation (stress vs strain) curves. These values have been obtained from in-house laboratory tests.

4.1.4 *Normal bond strength*

The outstanding feature of the membrane is its bond strength. When embedded into concrete it bonds on both sides promoting excellent watertightness, by preventing the development of water migration on both concrete-membrane interfaces, and facilitating shear connection properties.

The bond is provided by the membrane's polymer-rich cement base which prevents de-bonding and ensures the long-term stability of the system. The strong bond is given by crystals produced during the hydration of the cement. These crystals are embedded on the surface of cured concrete and grow into fresh applied membrane paste. The crystals are also embedded in the open exposed surface of the cured

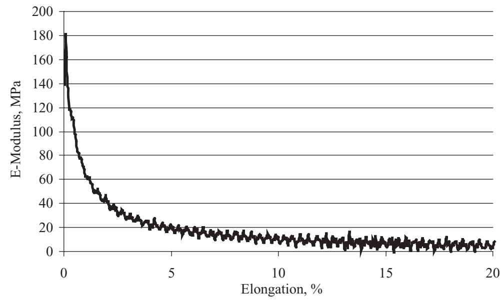

Figure 8. Stiffness values (*E*-modulus) plotted against elongation in percent of Masterseal® 345 dry membrane.

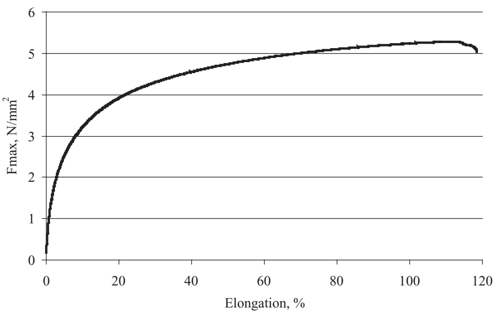

Figure 9. Tensile Force (Fmax) plotted against elongation in percent of Masterseal® 345.

membrane and grow into fresh applied concrete, providing the chemical and mechanical bond.

The bond is unaltered by the concrete placement technique, be it sprayed or cast insitu, or by the presence of fibers. Tests conducted in accordance with EN 1542 and EN 1766 show that the adhesive (normal) bond strength to clean and particle free cementitious materials is significant and easily reaches 1.2 MPa ± 0.2 MPa and reduces to 0.5 MPa when water saturated (Figure 10). The bond strength to metals ranges from 0.5 to 1.2 MPa.

4.1.5 *Bulk density*
Bulk density (+20°C) is 590 kg/m³ ± 100 kg/m³.

4.1.6 *Water vapor diffusion resistance factor*
Water vapor diffusion resistance factor, μ, of max. 300.

4.1.7 *Frost insulation*
The membrane itself 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 F100 in h/°C, the maximum number of

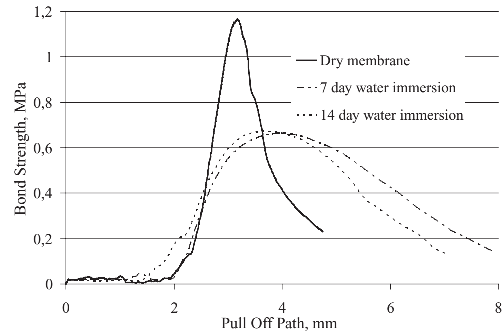

Figure 10. Adhesion of Masterseal® 345 to concrete.

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.

4.1.8 *Fire resistance*
The membrane does not contain any flammable components, in the event of a fire it is self-extinguishing. When exposed to higher temperatures, approximately 200°C, the membrane softens and then melts emitting carbon dioxide and water (vapor). In the event of a fire, and depending on the intensity of the fire, the damaged area within the tunnel may be refurbished by removing locally the damaged concrete lining and waterproofing. As the membrane melts the bond with the concrete on either side will be lost and restored once the temperature decreases as the membrane hardens once again.

5 COMPOSITE LININGS

The fully bonded nature of the membrane allows the lining to act as a composite structure wherever the primary sprayed concrete can be taken to contribute to the final lining. Great saving can be achieved over the traditional approach, by considering no part of the lining as a "temporary support", and by the reduction in excavation volume and lining material, which leads to a reduction in construction time.

In a real life situation the two linings behave either as a true "single-shell" or act monolithically through the deformation of the membrane, depending on the magnitude and direction of the applied loads (radial and tangential) and subsequent relative deformation of each lining layer.

The principle of composite action can be demonstrated by comparing the action of two joists placed one on top of the other. If these are simply placed one on top of the other and loaded as a beam there will be some relative movement between the two. However, if these are physically connected, the bending strength and stiffness are significantly improved as the two will act together as a single unit with combined thickness.

Traditionally, primary and secondary linings could be thought of as acting as a "single-shell" thanks to the shear connection provided by the roughness of the surface. However, an improvement in performance is achieved by connecting the primary concrete lining to the secondary concrete lining by means of a fully bonded membrane that can accommodate the shear forces. As with the so-called "single shell" approach (Golser & Kienberger 1997), it can be assumed the two sprayed concrete layers act together as a composite structure. Aside from the obvious waterproofing advantages, highlighted in section 3.1, a fully bonded membrane is therefore also structurally advantageous.

The capacity of the membrane to allow shear stress transfer across its section allows load sharing between sprayed concrete layers. The composite lining as a whole is able to withstand all potential loading conditions from the ground, ground water and surface loads throughout the design life of the tunnel and at the same time is watertight, durable, capable of accommodating the loads of internal structures such as lighting canopies and ventilation fans and have a surface finish to achieve the required reflectance and aesthetic appearance.

These interface properties are of particular importance and are currently being investigated. Some tests have already been performed, the results of which are discussed in Section 5.1, while other tests are on-going. The excellent bond allows it to be an attractive solution on new as well as on rehabilitation projects, including masonry and brick tunnels, where limited space presents an important issue. Composite linings are a flexible, logical, modern and economical solution.

5.1 *Interface properties*

To achieve truly composite behavior and guarantee the structural effectiveness of the system, a bond needs to be achieved between the concrete layers and the sprayed membrane to permit the transfer of normal and shear forces between the primary and secondary layers.

The bond strength required at the interface between the primary and secondary lining to permit the composite action required in so-called "single-shell" linings must be evaluated for each project. Studies are being conducted to address the question of the bond (normal and shear) strength required at the interface between the primary and secondary lining to permit the composite action. However, each project must consider the prevailing load conditions before coming to a judgment on whether or not a composite lining solution is achievable.

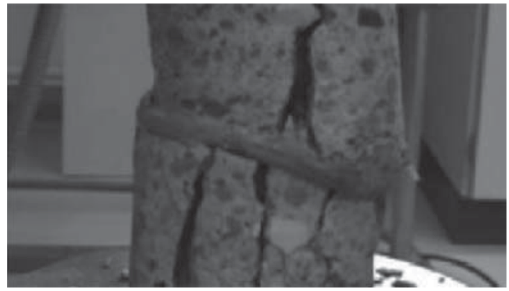

Figure 11. Masterseal® 345 membrane bridging over a considerable crack.

Relative creep and shrinkage movement of the two layers will cause stresses in the membrane. This may constitute an issue wherever the relative deformations are larger than the membrane's elongation potential, however, some movement can be taken by the membrane and it is expected that most of the movement in the primary lining will have taken place prior to the installation of the membrane and secondary lining. In order to define the whole system as working as a sandwich of sprayed concrete—waterproofing—sprayed concrete, an in-house research programme has already been initiated.

5.1.1 *Shear behavior*

When a shearing load is "slowly" applied to the composite structure, thanks to its particular chemistry, the membrane has sufficient time to adapt to the imposed deformation through the rearrangement of its molecules. In this case the membrane behaves in a viscous manner and is not compromised.

When load deformations are applied at higher rates, the composite lining resists with shear strength parameters given in Table 2. These shear strength parameters are taken from direct shear tests carried out under zero normal displacement conditions (constant normal load) to a 2 mm thick membrane applied to a smooth substrate and a 5 mm thick membrane applied to a rough substrate. These two specimen conditions have been taken from typical membrane consumption rates and thickness applications on actual projects and represent two ends of a spectrum, a float finished sprayed concrete substrate coupled with a minimum thickness of membrane and a rougher substrate coupled with a thicker membrane layer. Quantification of roughness is always difficult and in this case was done according to the Joint Roughness Coefficient (JRC) index. The smooth surface of specimen 00 has a JRC of 0 and the rough surface of specimen 03 JCR of 20 (Fig. 12).

Tests were performed once the membrane had been allowed to cure for a minimum of 28 days and the concrete to dry out (min. 4–6 hours, depending on environmental conditions).

Normal stiffness tests have been carried out by controlling the normal stress. Since, in a tunnel, loading is controlled by the displacement of the ground or existing lining, future tests will be carried out with controlled normal displacement, instead of the normal stress. Normal stiffness insitu depends on the specific application (stiffness of the ground and reinforcement/linings). To overcome this issue, direct shear tests at constant normal stress can give a complete constitutive behavior that includes mobilization of shear strength and dilatancy at each shear displacement.

5.1.2 *Bending behavior*

In-house Centre Point Load tests, in accordance with EN 12390: Parts 1 and 5, were undertaken on 6 month old (fully cured) specimens having thicknesses of Masterseal® 345 of between 2.5 and 4 mm.

Table 2. Results of direct shear tests.

Parameter	Specimen 00	Specimen 03
Masterseal 345 membrane thickness, mm	2	5
Sprayed concrete roughness	Plane saw cut	Shotcrete roughness
Joint Roughness Coefficient, JRC	0	20
Vertical modulus (first load), MPa	34.5	32
Vertical modulus (unload), MPa	56	40
Shear modulus, MPa	17.5	7.2
Maximum shear stress, MPa	1.01	1.7
Cohesion (c), MPa	0.5	1.05
Friction angle (ϕ),°	24	43

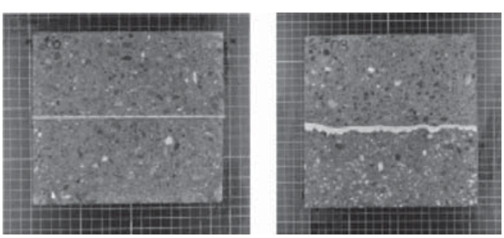

Figure 12. Two specimen blocks for the direct shear test. On the left the specimen with a 2 mm membrane sprayed onto a smooth substrate. On the right a 5 mm membrane sprayed onto a rougher substrate.

Flexural load actions are usually non-uniform, often arising from single-point loads, and involve interactions between several concurrent load actions, such as axial and shear stresses.

The results from these tests indicate the flexural strength and the post-crack performance in terms of residual strength or energy absorption. The specimens were produced by spraying a fiber-reinforced concrete mix with a maximum aggregate particle size of 10 mm. The minimum average flexural strength, f_{ct}, of the specimen without a membrane was 6 MPa and 3 MPa when the membrane is installed centrally with respect to the composite system. It is however evident from the results that, despite the flexural strength decreasing with the integration of a less stiff membrane, the post-cracking or residual flexural strength of a composite beam inclusive of a membrane is higher than that of an equivalent beam without membrane.

5.1.3 *Analysis*

An investigation of composite behavior was undertaken by Mott MacDonald to simulate composite action and examine the boundaries of its applicability.

The properties of the interfaces between the concrete and the waterproofing membrane were taken from a back-analysis of shear test data gathered at the Technical University of Graz. The original shear test curves were replaced with curves derived from FLAC (Fast LaGrangian Analysis of Continua) simulations of the shear tests. The input parameters for the model are derived by first back-analyzing this test data and calibrating the numerical model. The FLAC base model consisted of a 1 m thick length of composite tunnel lining with 280 mm thick primary lining, a 3 mm layer of Masterseal® 345 and a 145 mm thick secondary lining.

An external pressure was applied to the ring, simulating a vertical stress of 500 kPa and a horizontal stress of 1000 kPa (i.e. the ratio of horizontal to vertical stresses, $K = 2$). This represents

Figure 13. Centre Point Load test on a sprayed concrete specimen with a horizontal layer of Masterseal® 345 at mid section.

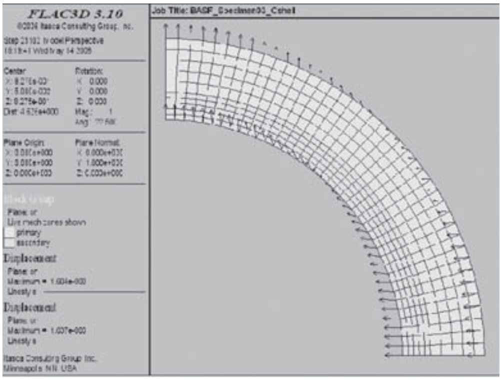

Figure 14. Composite tunnel lining with Masterseal® 345 interface in the FLAC 3D model.

a highly loaded tunnel lining, subjected to bending as well as compression. Most tunnels would experience lower loads than this.

The numerical modeling showed that composite action is possible with Masterseal® 345 and that the performance is relatively insensitive to the precise strength or stiffness values of the bond between the membrane and the concrete.

6 QUALITY CONTROL AND DURABILITY

6.1 *Quality control*

Sprayed concrete and sprayed membranes, as with any material constructed insitu, suffer the problem that there remain residual concerns about quality control and workmanship. However they have been successfully used on a number of projects. Recommendations for quality control test methods have been made and it is considered that a robust quality control system can be implemented on site. Pre-construction trials and training of operatives are vital for a successful application.

6.2 *Durability and waterproofing philosophy*

Masterseal® 345 is designed to be spray-applied in a sandwich system between layers of sprayed or cast concrete. This composite system is the key to optimum durability.

For example, in most applications this should limit the temperatures to which the membrane is exposed during its life and prevent exposure to UV radiation. Because this product has been on the market for a relatively short time definitive statements on durability cannot be made. However, this type of polymer has been used in construction for many years and is very stable chemically.

The membrane material consists of Ethylene-vinylacetate (EVA) polymers. In a tunnel environment, the only relevant decomposition mechanism for EVA is by thermal ageing. All materials show some limited rate of change of properties over time, depending on exposure to various conditions and environmental effects. However the chemical nature of polymer-modified mortars in outdoor and indoor exposure was examined by Schulze & Killermann (2000). Over a ten year period, the EVA copolymer gave stable adhesive, flexural and compressive strength. According to scanning electron microscopy (SEM) the morphology of the polymer in the mortars does not change over this period.

However, the long-term durability of a composite lining is more than the chemical durability of the membrane material itself and involves an understanding of which failure mechanisms can potentially occur. An intact and complete sandwich structure is essential to avoid mechanisms which can lead to failure over time. Thus maximization of the structural durability and watertightness of sprayed concrete is possible through the minimization of the potential for water paths through cracks or construction joints, and also by considering the appropriate sprayed concrete mix design to reduce permeability. Water permeability and oxygen diffusion tests from numerous projects have demonstrated the low permeability of sprayed concrete despite the addition of accelerator, super plasticizer and stabilizer/retarder admixtures which are currently essential components of the wet-mix design.

Steel fiber reinforcement has often been used to replace conventional welded steel mesh in permanent sprayed concrete linings to provide additional material safety by reducing shadowing and maintaining early age thermal cracking down to 0.2 mm. Of particular benefit to a lining supporting the ground is the ductile nature imparted by the steel fibers. This allows greater redistribution of loads in the lining, and should the tunnel lining crack, considerable residual strength will exist, thus allowing time to implement contingency actions if necessary.

7 CASE HISTORIES

Composite linings as ground support and waterproofing systems have been adopted as the functional waterproofing and tunnel support on many projects worldwide including the recently constructed Viret Tunnel as part of the Lausanne Metro M2 in Switzerland and the concrete lined Chekka Road Tunnel in Lebanon (rehabilitation project). The design of these tunnel linings comprises both drained and undrained solutions.

Sections of the Hindhead A3 Tunnels and Thames Water's Hampton Shaft, in the UK, have also been designed using this ground support and waterproofing system. Details of some of these and other projects are discussed below.

7.1 *Giswil tunnel*

An emergency escape tunnel running parallel to the 1960 m long Giswil road tunnel in central Switzerland was excavated by a 4.0 m diameter hard-rock TBM through mica schists. A length of approximately 10 m at each end of the tunnel was excavated by drill-and-blast. In the portal areas a cut-and-cover concrete tunnel was constructed.

A waterproofing solution was required that provided no water ingress into the bored part of the tunnel, a successful solution for waterproofing continuously from the bored tunnel, through the blasted part of the tunnel to the cut-and cover concrete tunnel at the portal. Compatibility between the waterproofing methods was required. An undrained solution, with a waterproofing system that covered the full tunnel profile, including the invert, was proposed.

The main advantages of proposing a spray applied fully bonded membrane (Masterseal® 345) were: high bond strength to concrete preventing migration of water along the membrane/substrate interface, hence significantly reducing the risk of water seepage even by eventual damage or holes in the membrane; the feasibility of waterproofing the invert; the feasibility of waterproofing the interfaces between bored tunnel and drill-and-blast excavated tunnel, as well as between drill and blast excavated tunnel and concrete cut and cover tunnel; compatibility with the PVC sheet membrane at the interface with the running tunnel; and injection rather than drainage could be performed for removal of water seepages due to the adoption of an undrained solution.

The removal of water seepages around the tunnel profile, which would otherwise cause problems with the bonding of the membrane to the substrate, was done by means of one-component polyurethane injection and two-component acrylic injection (Fig. 15). Manual application of an optional smoothing layer of sprayed concrete was applied to limited sections with a 4 mm maximum grain size to provide a suitable substrate for cost-effective spray membrane application (Fig. 16). Removal of the remaining water seepages through the substrate was implemented by small scale acrylic injection (mainly sealing/filling of dripping bolt holes) (Fig. 17). These injection works were done successfully and with very limited effort. The Masterseal® 345 waterproofing membrane, minimum thickness 3 mm, was sprayed onto the crown and walls (Fig. 18). Frequent spot thickness controls with needles were done during spraying (minimum every 2 to 3 minutes). The nozzleman was always kept updated as to the effective thickness which was sprayed. Average capacities of 70–80 m^2 per hour were achieved.

Figure 15. Temporary removal of water seepages before applying the sprayed concrete substrate (Giswil tunnel).

Figure 16. Application of sprayed concrete to the substrate via MEYCO Oruga manipulator prior to the spraying of the membrane (Giswil tunnel).

Figure 17. Before the spraying of membrane: removal of the last drip spots through rock bolt holes with injections with MEYCO® MP308 (Giswil tunnel).

Figure 18. Set-up for the application of Masterseal® 345 with MEYCO® Piccola dry sprayed concrete machine (Giswil tunnel).

Figure 19. Application of the inner concrete layer with wet-mix sprayed concrete (Giswil tunnel).

Spraying of the unreinforced inner concrete layer was then effected, design thickness 10 cm to the crown and walls. The spraying of the inner concrete took place 1 day after the application of the membrane (Fig. 19). A 150 mm horizontal strip of membrane in the lower wall was left exposed. This ensured overlapping and a continuous membrane when applying the membrane in the invert. Thorough cleaning of the invert was necessary in order to facilitate spraying of the membrane in the invert.

Application of the membrane to the invert was achieved by careful spraying. An overlapping horizontal strip of membrane in the lower wall ensured a complete coverage of the tunnel perimeter. Finally the sprayed concrete could be applied in the invert.

The unique features of the sprayed membrane were clearly manifested during the Giswil project. Its versatility in being compatible with other waterproofing systems and tunnel support systems were demonstrated. Furthermore, due to the bond it offered, the opportunity existed for construction of an economical composite single shell lining reduced the risk of uncontrolled water paths typically associated with PVC membranes. A test five years after construction showed that the tunnel was dry and still withstood 4.5 bars of hydrostatic pressure.

7.2 *Tunel de Viret, Lausanne Metro*

The new M2 Metropolitan Railway Line was designed to cross Lausanne from South to North. The urban sections were built in 8 tunnels using "cut and cover" construction techniques and the rest as partial face tunneling. Two of these tunnels, including the 275 m long Tunnel de Viret, were waterproofed with Masterseal® 345 spray applied membrane (Fig. 20). The primary lining consists of steel arches and mesh followed by a 25 cm thick layer of sprayed concrete.

Figure 20. Masterseal® 345 applied to the entire tunnel contour. A final lining of 30 cm sprayed concrete was applied on top of the membrane (Tunnel de Viret).

Originally, sprayed concrete, a traditional PVC sheet membrane and a final lining of cast in-situ concrete were specified for the two tunnels. The alternative solution involved a spray applied waterproofing membrane and an inner lining of fiber-reinforced sprayed concrete (Fig. 21). In terms of construction, this resulted in a considerable amount of time being saved. Furthermore, no shutters were required for the inner shell of concrete. The sprayable membrane alternative proved to be more cost-effective for the project overall compared to a technical solution with sheet membrane.

The primary sprayed concrete lining surface was very rough however no smoothening layer was applied and any large holes were repaired with mortar. Local dripping water was managed via minor polyurethane injection through small hoses fitted in holes drilled in the primary concrete (Fig. 22). Final waterproofing of the tunnel profile was carried out using the Masterseal® 345 spray applied membrane (sprayed to a minimum thickness of 3 mm, Fig. 23).

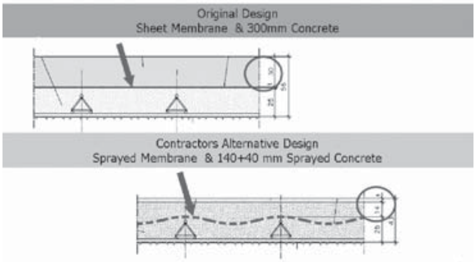

Figure 21. Comparison between original and alternative design (Tunnel de Viret).

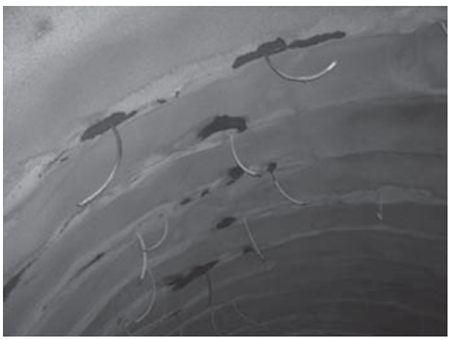

Figure 22. Temporary drainage of water seepages through drillholes and small packers (Tunnel de Viret).

Figure 23. Manual application of Masterseal® 345 (Tunnel de Viret).

A total of 140 mm of sprayed concrete was then applied to the membrane as the inner layer. A 40 mm thick smoothing layer was applied to ensure a good surface finish (Fig. 24). Masterseal® 345 works even on a rough surface with some water but more time is required for surface preparation and wet spot management. Good preparation works were essential. Temporary water drainage is needed for Masterseal® 345 application in the invert. Considerable benefits in terms of savings on material and time were gained. The construction time was reduced by 3 months.

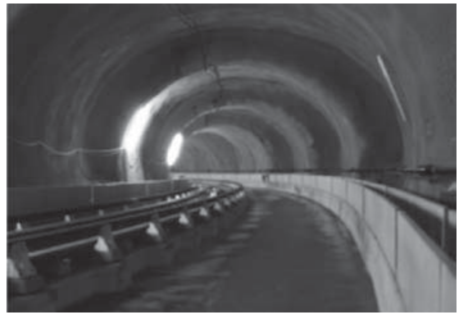

Figure 24. Finished tunnel with composite waterproof liner with Masterseal® 345 and sprayed concrete (Tunnel de Viret).

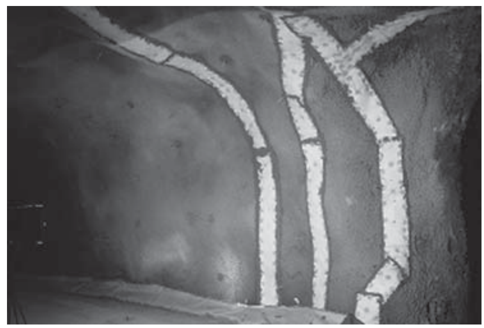

Figure 25. Wet spot management prior to spraying the membrane (Hirtenberger Ammunition Caverns).

7.3 *Clem Jones Tunnel, Brisbane*

The Clem Jones Tunnel is a dual road tunnel providing a direct cross-city link bypassing the CBD. Formerly known as the North-South Bypass Tunnel, the Clem Jones Tunnel (CLEM7) at 6.8 km in length is Brisbane's first major road tunnel. The project features twin two-lane tunnels, including a section up to 60 m below the Brisbane River bed. The main tunnel is a segmentally lined bored tunnel. The contractor was looking for a new, efficient and cost-effective way of waterproofing the cross-passages and intersections with the running tunnel. The tunnel cross passages were waterproofed using a sprayed membrane. The detail at the interface with the segmental lining is illustrated in Figure 6.

7.4 *Refurbishment of the Hirtenberger Ammunition Caverns, Austria*

In Hirtenberger a cavern system is used to store explosives underground. This facility, which was

Figure 26. Application of a smoothing layer prior to spraying of the Masterseal® 345 waterproofing membrane (Hirtenberger Ammunition Caverns).

Figure 27. Manual spraying of the Masterseal® 345 membrane (Hirtenberger Ammunition Caverns).

about 20 years old, needed a complete refurbishment since the concrete was already partly disintegrated and the caverns could only be used to a limited extent. Since the caverns varied substantially in length, width and height (length 20–58 m, width 5–6 m, height 4–5 m), the designer proposed permanent fiber reinforced sprayed concrete and a fully bonded sprayed membrane for the refurbishment.

After some structural repair was done to the existing lining, a smoothening sprayed concrete layer was applied. Dripping water was channelled and fed into the drainage system by using drainage strips (Fig. 25). Sheet membranes were used for waterproofing of the invert. The Masterseal® 345 sprayed membrane was then applied in the crown and walls (Figures 26 and 27) and connected to the invert's membrane by simple over-spraying. After some curing time a 10–25 cm thick steel fiber reinforced sprayed concrete was placed as the inner lining.

8 CONCLUSION

A wide variety of options exist for tunneling methods and linings. A systematic evaluation of risks can help choose the most appropriate ones. As demonstrated by the recent experiences documented in this paper, an extremely efficient solution for waterproofing has been successfully provided through a fully bonded waterproofing membrane. Where the use of sprayed concrete can be considered as a permanent solution, additional structural benefits can be gained through composite action.

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