COMPOSITE SHELL LININGS

EINSCHALIGE TUNNELAUSKLEIDUNGEN

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Over a series of major projects our company has developed design solutions for the use of permanent sprayed concrete with a variety of waterproofing solutions. This has ranged from permanent sprayed concrete, sprayed onto a sheet membrane in a drained tunnel, permanent waterproof sprayed concrete in impermeable ground and permanent sprayed concrete, sprayed in two passes with a spray-applied waterproofing membrane in between for cases where there is a higher risk of water ingress. We have examined the composite action of the last case and found that significant load sharing can be obtained, even with modest bonding at the membrane interface. The issues related to the design of composite linings and the range of suitability will be discussed in the paper, along with examples from recent projects. New developments are continually occurring and the latest thinking on composite linings will be presented. This technology has a role to play in certain situations and is a useful addition to the armoury of tunnel engineers.

Im Zuge mehrerer bedeutender Projekte hat unsere Firma Konzepte zur Umsetzung von permanenten Spritzbeton-Auskleidungen, mit unterschiedlichen Ansätzen zum Abdichtungs-system, entwickelt. Diese Konzepte umfassten Spritzbetoninnenschalen auf Folienisolierung in Tunneln mit Bergwasserdrainage, wasserdichte Spritzbetoninnenschalen in relativ wasser-undurchlässigen Böden und zweischalige Spritzbetonauskleidungen mit Spritzfolie zwischen den Schalen in Fällen mit größerem Risiko für Wassereintritte. Die Verbundwirkung für den letzten Fall wurde untersucht und dabei herausgefunden, dass auch bei nur geringem Verbund in der Fuge zur Membran, eine Mitwirkung beider Schalen an der Verbund-konstruktion möglich ist. Fragen bezüglich der Statik von Verbundschalen und die Bandbreite eines sinnvollen Einsatzes werden in diesem Beitrag auch anhand aktueller Beispiele diskutiert. Laufend gibt es Neuentwicklungen und die neuesten Ideen werden daher ebenfalls angesprochen. Diese Technologie hat bei speziellen Einsatzzwecken Bedeutung und ergänzt daher die Werkzeugkiste desTunnelbau-Ingenieurs.

1. **Introduction** (1 to 4 previously published in [2])

Traditional methods of sprayed concrete lining (SCL) tunnels (in soft ground) comprise a temporary primary lining of sprayed concrete with a sheet membrane inside and a permanent cast insitu concrete lining, usually reinforced with steel bars. Even now, although it is widely accepted that sprayed concrete can be used as a permanent material, the traditional methods are applied to the majority of tunnels. This is wasteful in terms of money, time and materials. This paper will present how our company is now providing design solutions for the use of permanent sprayed concrete with a variety of waterproofing solutions through our involvement as designers on major projects in the UK. The context of this discussion is soft ground tunnelling, where the profile of the ground can be cut quite smoothly.

The design solutions have ranged from permanent sprayed concrete, sprayed onto a sheet membrane in a drained tunnel, permanent waterproof sprayed concrete in generally impermeable ground and permanent sprayed concrete, sprayed in two passes with a spray-applied waterproofing membrane in between for cases where there is a higher risk of water ingress.

This paper will concentrate on the last case. Having examined the composite action, it has been found that significant load sharing can be obtained, even with modest bonding at the membrane interface.

The issues related to the design of composite linings and the range of suitability for different functional requirements will be discussed in this paper, along with examples from recent projects of shallow tunnels in soft ground or weak rock.

This paper will also report on initial findings from preliminary testing with BASF exploring single shell tunnel lining solutions and bond strength between a sprayed membrane with permanent lining to demonstrate a greater composite action. This, coupled with some discussion on the most recent numerical modelling from a live project, will outline where sprayed concrete lined (SCL) composite lining solutions are heading, expanding on the challenges that will have to be met to handle different situations as well as satisfying functional requirements to clients and the wider tunnel industry.

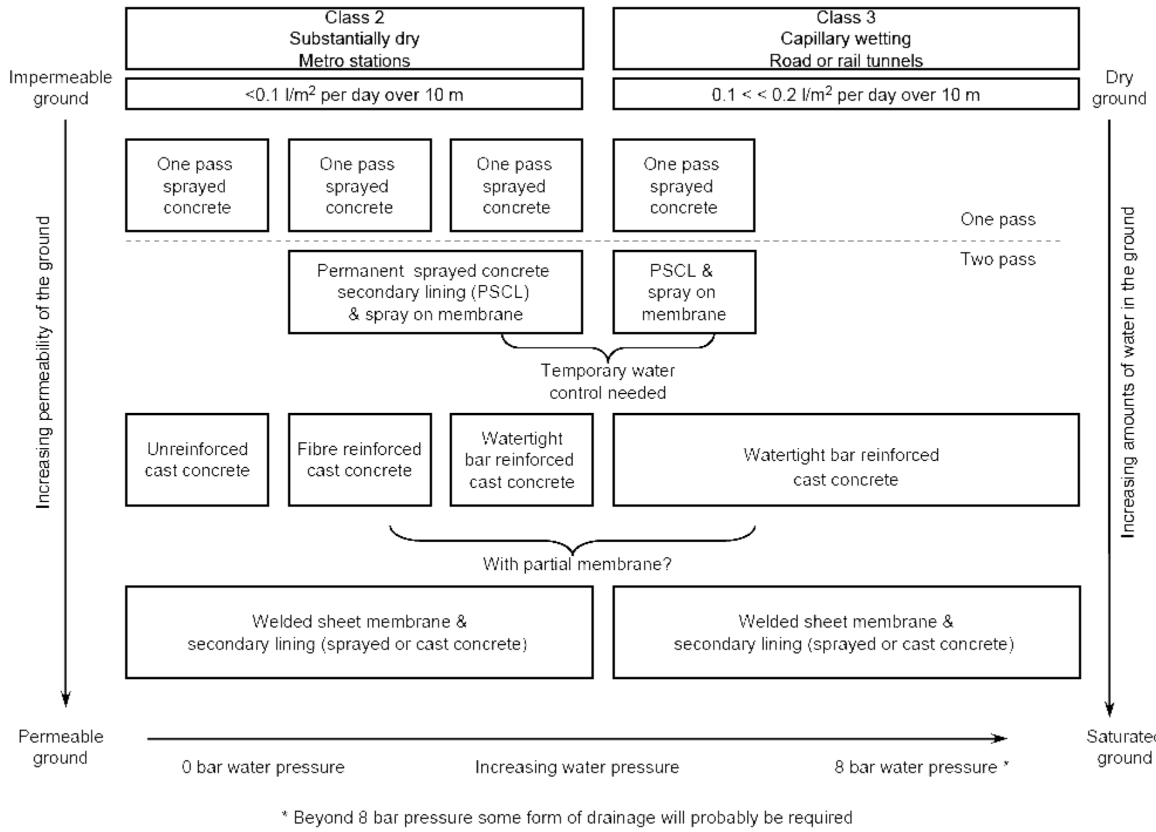


Figure 1: Design options for linings and waterproofing [1]

2. Design options

There are now several options for SCL tunnels open to tunnel engineers to suit different geological and hydrological conditions and/or the Client's functional requirements (see Figure 1 – [2]). The SCL options can be broadly categorised into three types: Double Shell linings (DSL) which assumes a sacrificial primary lining which takes the temporary loads and a secondary lining to take the permanent loads. This has significant pedigree however because the primary is considered temporary the secondary is designed to take both long term ground loads and hydrostatic, thereby while providing a robust design it is a lot thicker than CSL types, this is discussed in more detail in [2].

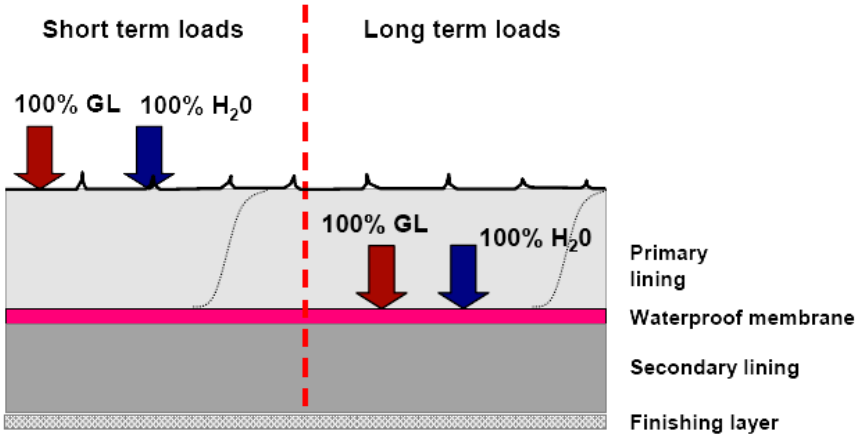


Figure 2: Typical Double Shell lining

Composite shell linings (CSL) where the primary lining will take the temporary loads and a proportion of the permanent load through composite action with the secondary lining and a Single shell lining (SSL) where one lining takes the temporary and permanent loads – although this one lining may be built up in several passes. In most cases a waterproof membrane is employed to provide a watertight structure (in CSL solutions this is generally between the primary and secondary linings). The different types are described in more detail in sections 2.1 to 2.2.

2.1 Composite Shell Linings (CSL)

Through recent projects such as A3 Hindhead road tunnel [3] and Thames Water Hampton shaft, all in the UK, the use of sprayed waterproof membranes have given engineers an opportunity to explore the benefits of a composite shell lining, i.e. a sprayed permanent primary lining, sprayed waterproof membrane and a sprayed secondary lining, where the primary lining acts compositely and takes a proportion of the long term ground loads. A key step that had facilitated this leap forward has been use omission of lattice girders and the use of laser profiling systems to control the shape of the tunnel during construction [3]. Lattice girders are usually not regarded as structural members but they have been seen as essentially in controlling the shape of the tunnel. They are notoriously difficult to spray around and leaks – and therefore corrosion – often occur at the location of the lattice girder. Removing girders removes both a corrosion problem and also reduces the need for men to work at the face when the full support is not in place.

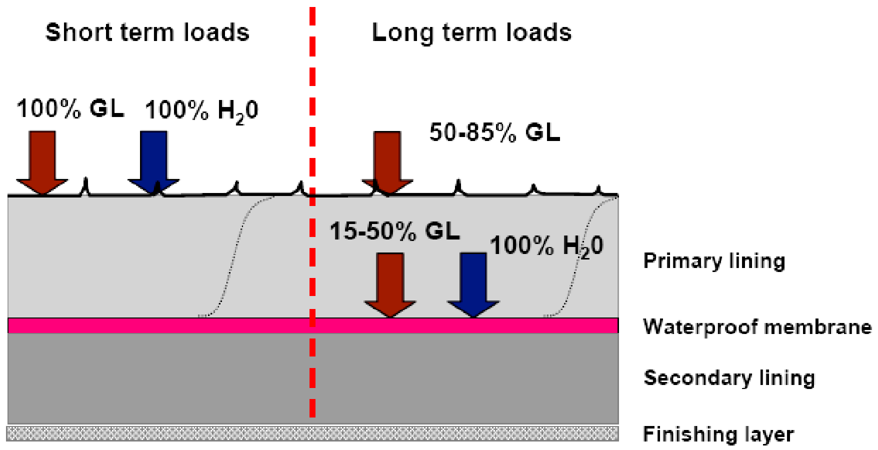


Figure 3: Typical Composite Shell Lining (partial composite with no shear or adhesive bond)

Composite linings are now being incorporated into major UK projects, typically under the following design conditions, as shown on Figure 3:

- 100 % Ground and hydrostatic loads applied to primary lining in the short term
- The option of load sharing for the ground loads in long term
- Full hydrostatic load applied to secondary lining in the long term
- No bond or shear capacity between linings is used in the structural design

This design methodology has resulted in some reductions to the thickness of the secondary lining when compared to conventional Double Shell Linings but this is fundamentally limited by the assumption that the water pressure acts on the membrane. For a shallow tunnel in soft ground, the water load is similar or even exceeds the ground load. The percentage of ground load on the secondary lining is usually determined from numerical models and it varies depending on the loading behaviour of the ground. In materials such as clay, there is a distinct short and long-term behaviour, while in others there may be little or no change in the loads over the lifetime of the project from the loads generated during the construction period. In other words, without some consolidation or rheological behaviour in the ground, the secondary lining may not experience much of the ground load.

In one recent project, the first layer of sprayed concrete – the so-called sealing layer of 75 mm sprayed concrete – is regarded as temporary and omitted from the design in the long-term. This was due to concerns over sulphate attack and poor quality when spraying on to the excavated surface.

Presently there is further study and testing being undertaken to demonstrate a fully composite lining discussed in section 4, as shown in Figure 4, i.e. shear and bond strength at the interface of the waterproof membrane, once this is ascertained further reductions could be achieved for the thickness of the secondary lining.

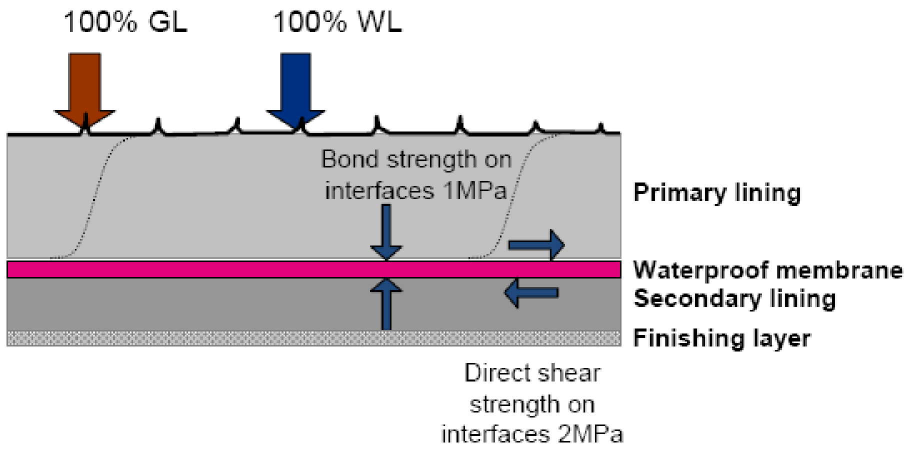


Figure 4: Fully Composite Shell Lining

- Composite action between linings by achieving shear capacity across membrane-concrete interfaces
- Load sharing for the ground load and water load (WL) in long term
- Full hydrostatic load applied to secondary lining in the long term
- Bond strength on membrane interfaces to be 1 MPa
- Shear strength on membrane interfaces to be 2 MPa

The advantage, as discussed above, is the reduction to secondary lining thickness without compromising the watertightness requirement. The main disadvantage is there is currently no precedence for a fully composite lining with a spray applied membrane. However, single shell permanent sprayed concrete linings have been successfully used on a number of projects such as Heathrow Terminal 5 [1, 4 & 5] and the design for Hindhead considered both load cases - with and without full composite action.

2.2 Single Shell Lining

Single Shell Linings offer the most efficient lining design (in dry or largely dry ground) as they take both the temporary and long term loads and the construction is very fast compared to a double shell or composite lining where there are both primary and secondary lining stages to the construction. Single shell linings have been widely used in the hydropower sector and in all tunnelling sectors in certain countries, most notably Norway.

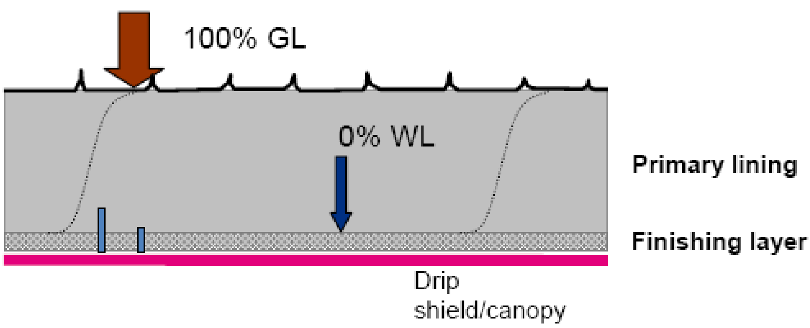


Figure 5: Typical Single Shell Lining

- No waterproofing membrane
- Ground loading all on primary lining
- No hydrostatic load
- Watertight concrete design – but allows local seepage
- Optional drip trays provided outside architectural cladding

The main disadvantage is that Clients will tend to opt for watertight tunnels thereby avoiding operation and maintenance issues and drainage systems. Unless the ground is dry or generally impermeable – such as London Clay – it is hard to achieve watertight tunnels with Single Shell Linings. That said, this can still remain as a design option for non-public tunnels where lower levels of watertightness are acceptable.

3. Composite shell lining – design philosophy

For recent projects there has been a push to mechanize sprayed concrete lined tunnel construction as much as possible and thereby removing tunnel operatives from the face of the tunnel, decreasing the risk of death or injury as a result of tunnel collapse, being hit by falling sections of the newly sprayed lining ("sloughing") or risks associated with fixing reinforcement, lattice girders and sheet waterproof membranes at height. Therefore with the precedent set from the A3 Hindhead tunnel construction, the lining design of sprayed primary and secondary linings with steel fibre reinforcement (SFRS) and shape control techniques that remove the requirement for Lattice Girders and a sprayed waterproof membrane, has been adopted for major SCL works in the UK where geological conditions are suitable. At present little guidance exists on this subject so the features of this composite lining design are described in more detail below:

3.1 Primary Lining

The permanent primary lining is designed to take the full short-term applied ground load and any other loads, such as compensation grouting and surface surcharges, expected in the two to three years prior to secondary lining installation. Any additional long-term loads, such as consolidation or creep in the ground, will be shared between the two linings, subsequent to the installation of the secondary lining. The loading is determined using sophisticated numerical models.

The primary lining is designed as a sprayed concrete lining containing structural fibre reinforcement. The structural fibres are to increase the ductility of the concrete and provide toughness and post-crack resistance in the long term (see section 3.4). Conventional bar reinforcement is only required at openings and some headwalls. Smaller diameter bars (typically less than 12 mm) can be encased fully in sprayed concrete without too much difficulty. Larger bars (up to 25 mm) have been used successfully in permanent sprayed concrete. Nevertheless, the concept is to minimize the corrosion risk by removing and limiting bar reinforcement wherever possible. The use of laser survey shape control has been a critical step forward as explained earlier, since it has removed the major corrosion concern of lattice girders.

The use of fibre reinforcement and the specification of durable sprayed concrete constituents ensure that the lining will retain its strength and durability properties in the long term and so all but a small thickness of the primary lining is load bearing throughout the design life of the structure. The initial layer of 75 mm, which is sprayed directly against the ground, is considered as sacrificial and omitted from load capacity calculations in the long-term.

Typically the strength requirements for the sprayed concrete is C32/40 (i.e. a minimum characteristic cylinder strength of 32 N/mm²) but measured at 90 days. The same concrete should achieve 28 N/mm² at 28 days and exceed a modified J2 curve in the first 24 hours (as per EN 14478). The reduced strength at 28 days was deliberately chosen since it is known that, with modern accelerators, a high cement content is needed to meet the early age strength requirements and the concrete will continue to hydrate beyond 28 days. If a too high 28 day strength is set then, the concrete will "overshoot" this considerably in the long-term, which the high strength introduces a new set of problems related to brittleness and under-performance of the fibres.

3.2 Secondary Lining

Taking into account the loads and stresses already taken by the primary lining, the secondary lining is designed to carry:

- The full long term water pressure (see section 4)
- Internal loads, such as mechanical and electrical equipment
- Part of the long term ground load; e.g. the effects of consolidation
- The effects of temperature and shrinkage
- The effects of degradation of the primary lining (the sacrificial initial layer)

The proportion of ground loading applied to the secondary lining has been calculated using numerical modelling methods as the proportion of load carried by each lining will potentially differ: depending on the combination of geological conditions, the sequence of construction, and the lining system. Due to uncertainties over the mechanical properties of the bond between the membrane and concrete, the conservative working assumption is that there is no shear or adhesive bond at this interface. Obviously this limits the ability for the linings to share the loads, particularly the assumption of "full-slip" on the interface.

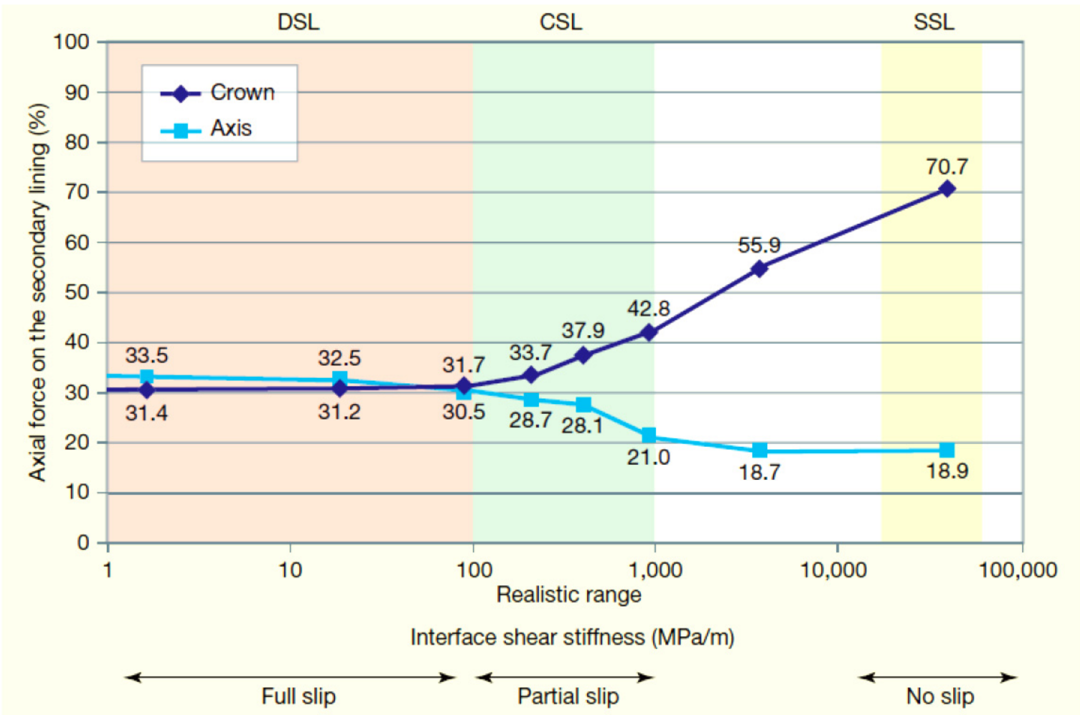


Figure 6: The hoop load in a secondary lining vs. the shear stiffness of the interface with the primary lining [9]

Analysing the effects of composite action is more complicated than it might appear at first sight, since in cases of uneven loading the behaviour varies around the lining. Figure 6 shows how the loads in the secondary lining can vary depending on the shear properties at the interface, for a simple model of a circular tunnel under uneven loading. More details on the numerical modelling study on which this figure is based can be found in [9]. Even under a relatively extreme combination of horizontal and vertical loads on a tunnel lining, no de-bonding in the normal direction was found so this suggest that the adhesive bond is only important in the temporary case during the spraying of the secondary lining. In the course of other design calculations, it has been found that the percentage of ground stresses carried by the secondary lining varies been 15 to 50 %. This is a function of the ratio of horizontal to vertical stresses, the lining thicknesses and the tunnel shape as well as the interface properties. The load-sharing is less pronounced in the design models for real tunnels because of the interaction with the ground, notably the tendency for the stiffer CSL lining to attract more load overall but at the same time less is applied to the secondary. The loads in the primary tend to remain broadly similar but the reduction of bending moments in the secondary lining of up to 20 % could permit a thinner secondary lining.

The secondary lining will be structural fibre reinforced sprayed concrete. Bar reinforcement is generally required at openings and some headwalls.

Secondary linings are typically designed to carry sufficient residual capacity to resist ground loading after a EUREKA time/temperature fire curve, as defined in the Technical Specification for Interoperability – Safety in Railway Tunnels (TSI-SRT). The EUREKA curve has been developed for the rail industry in Germany and is considered the most appropriate to the predicted fire scenarios. The secondary lining concrete (cast in-situ or sprayed) will contain micro-synthetic fibres in order to limit explosive spalling and maintain structural integrity. The quantity of fibres is typically determined by pre-construction testing and a dosage of about 1 kg/m^3 is normal. It has been shown in extensive fire testing for projects such as Heathrow Terminal 5, A3 Hindhead, and CTRL that the inclusion of micro synthetic fibres in high strength, low permeability concrete mixes significantly reduces the risk of explosive spalling when exposed to severe hydrocarbon fires.

3.3 Waterproofing Systems

Spray applied waterproofing membranes have been selected due to the benefits they can offer by bonding to both the primary and secondary linings. This property is advantageous as it offers maintenance and repair benefits in the long term by preventing the movement of water, either behind or, should it be breached, in front of the membrane. Should a leak be found on the surface of the secondary lining, as water is not able to move laterally, the source will be easily located and treated at that location in the primary lining also.

In water bearing stratigraphy, such as the Lambeth Group or River Terrace Gravels in London there is still a tendency for Clients and Designers to opt for a sheet waterproof membrane. Sprayed concrete can be applied to sheet membranes – for example: Thames Tunnel, UK; Russia Wharf, Boston, USA or Dulles Airport, USA.

3.4 Reinforcement

Reinforcement of the linings will be provided by structural fibres in the sprayed concrete matrix in combination with steel bar reinforcement located around junctions and openings.

Fibres – steel or macro-synthetic – add a modest tensile capacity. This can be incorporated into the design using a simplified stress block, for example, as described by [8] and shown in Figure 7. Various design approaches have been adopted on different projects, partly reflecting the confidence of the client or designer, as much as the state-of-the-art. Traditionally, Approach 1 was used and no benefit from the fibres was assumed. Clearly this is incorrect and unduly conservative. In Approach 2, the fibres are seen as guaranteeing the inherent tensile strength of the concrete. This approach offers little benefit in design since the tensile capacity up to first crack is so small. The approach adopted most recently is Approach 3, in which a simplified stress block, with a value of 0.37 $f_{ctm.fl}$, is used, based on [8]. This is conservative itself since the stress at first crack is 20 % higher than this value, which corresponds to the residual value at the end of a standard beam test. RILEM [8] recommends limiting the strain to 2.5 %; the strains in a standard 75 mm beam test are higher than this at a deflection of 2.0 mm.

In practice the Ultimate Limit State does not necessarily govern. Crack widths in the lining should be less than 0.3 mm and this curtails the contribution of the fibres to tensile capacity under Serviceability Limit State conditions. The subject of crack widths still requires some development. Methods are suggested for predicting crack widths (such as in [8]) but naturally, since this is a new material, the spacing and development of cracks within fibre reinforced concrete is not as well understood as in conventional bar reinforced concrete.

In the past specifications have often prescribed a dosage of fibres – for example, in permanent linings typically 30 to 40 kg/m³ of steel fibres. This is at odds with the normal practice in most other areas of setting performance specifications. Following the style of RILEM, sprayed concrete can now be specified in the following manner:

C28/35 FL 1.7

Which means the 28 day cylinder strength should be 28 MN/mm^2 with a flexural tensile strength of more than 1.7 MN/mm^2 at a strain of 2.5 %, which corresponds to a central deflection of 3.0 mm on the standard beam test. EN 14487 [6] offers another alternative:

C28/35 S 1.7 D 3.0

But this should be modified to add define the limits to one decimal place. Using whole numbers is simply too coarse a categorization.

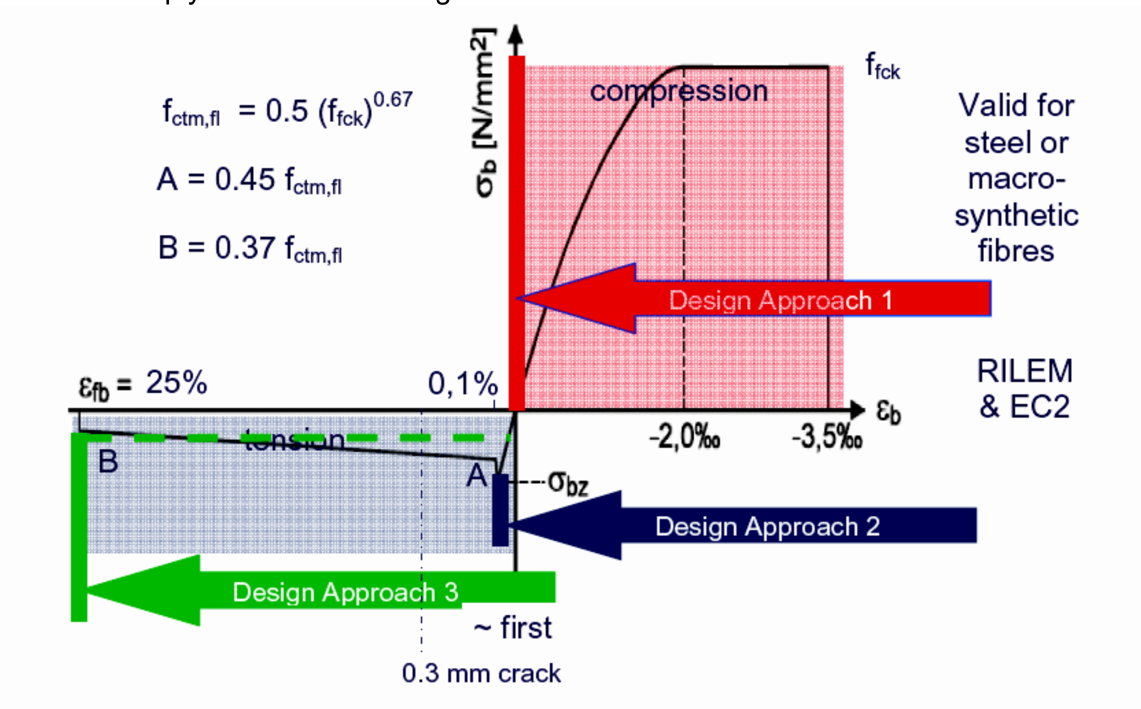


Figure 7: Simplified stress-strain models for fibre reinforced concrete

For large bending moments, steel bars remain the only realistic option. At this point it is worth mentioning that, on one recent project, a conscious decision was made to minimize the bending moments in the linings by adopting tunnel cross-sections that are almost circular, rather than adding bar reinforcement. The other possibility is to use thicker linings. Spraying some extra concrete is simple and quick and therefore the saving in time and materials compared to adding bars outweighs the additional cost of the extra concrete. This also minimizes the exposure of workers to activities near the tunnel face where the ground is only supported by the initial layer.

A fierce debate is raging between suppliers of steel and macro-synthetic fibres. The promotion of the virtues of their own products is natural and healthy competition. However, some of the negative marketing is less helpful to designers and constructors. Both products have strengths and weaknesses. The latter – most notably corrosion of cracked sections for steel fibres and creep for macro-synthetic – deserve to be examined in detail dispassionately. Macro-synthetic fibres are a viable alternative and the issue of creep is unlikely to be relevant at the low stress levels that are inevitable when normal factors of safety are applied. Similarly, the necessity to limit crack widths and the benign environment in most tunnels means that corrosion of steel fibres is unlikely to be a significant issue. As a final remark, one should be careful of extrapolating the results of standard beam tests – where there is limited opportunity for load redistribution – to tunnel linings which in statically terms are highly redundant shells which can redistribute loads very effectively.

4. Improvements

An obvious first improvement would be to use the bond strength of the spray applied membrane in a fully composite shell lining (see Figure 8). As discussed earlier this would led to more effective load sharing and a thinner secondary lining. Sufficient evidence exists for effective bonding on both sides of the interface at the membrane, see section 5. Only a modest bond is required for full composite action and the performance of a product can be verified by simple tests.

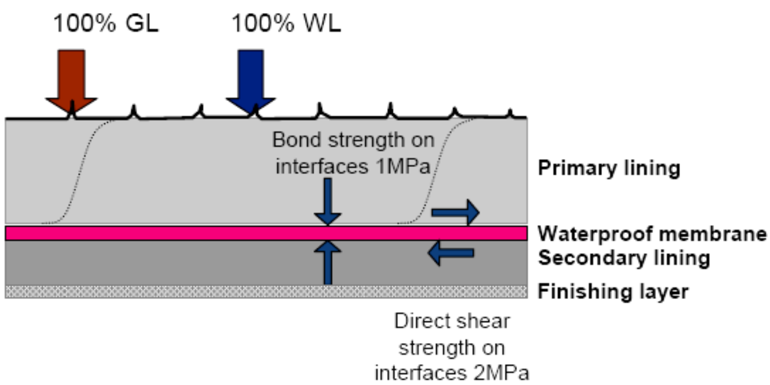


Figure 8: Fully Composite Shell Lining

The real Achilles heel of composite shell linings remains the position of the waterproofing layer which is more or less in the centre of the lining. A simplistic interpretation of this implies that in the long-term the first layer of sprayed concrete is saturated with water while the secondary is dry. The primary lining has joints at every advance length and, although in principle the concrete can be just as good here as anywhere else, in practice, cracking and water paths are likely to form there. In turn this leads to the conclusions that the water pressure in the ground is applied at the location of the waterproofing layer and that reinforcing bars – which might be needed for example at junctions – should not be placed in the primary layer as they may suffer corrosion. Both design assumptions are questionable but a more elegant solution would be simply to place the waterproofing layer on the outside of the lining, directly against the ground (Figure 9).

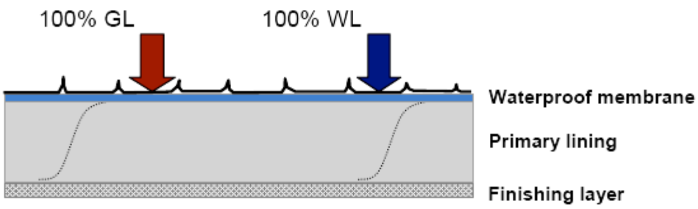


Figure 9: Single Shell Lining with waterproof membrane

This has the advantage that it fulfils Client requirements for a waterproof tunnel and reduces the overall lining thickness as per the conventional Single Shell lining. The salient features are listed below.

- Application of a waterproof membrane that also has ground support properties to provide safe entry to face and also watertight primary lining
- All ground and water loads act on the primary lining for the design life
- Requires continuous connection of "super skin" membrane between construction rounds
- During construction phase, any observed seepage through primary lining managed in collection channel and brought down to an evaporative drainage channel
- The suitability of the membrane is dependent on the geology and technology available, for example, presently not suitable for water bearing stratigraphy such as sands.

Thin Skin Liner (TSL) or so-called "Super skin" products, such as Masterseal 865 or Tamseal, could fulfil the dual role of an initial sealing coat to provide safe access to the face before the primary lining is sprayed and the first line of defence against water ingress. This technology has been around since the 1990s and has been trialled in the mining industry as a structural support or, in coal mines, to prevent methane ingress. Yilmaz [10] contains a good review of various TSL products and their properties. 5 mm of "medium" strength TSL is equivalent to 50 mm of SCL, in terms of structural performance at 1 day old. Achieving a substantially impermeable layer on the extrados of the tunnel, outside impermeable permanent sprayed concrete, would obviate the need for a secondary lining. The primary lining would carry all water and ground loads in both short and long-term. If necessary, a finishing layer could be applied later for aesthetics or fire protection. This represents the ultimate solution in terms of efficiency and sustainability. Trials are ongoing to investigate the best technologies to achieve this. This is discussed further in section 5.

5. Single Shell Lining – A practical application

For a single shell lining as described in Section 4 to be a viable option (and thereby provide a significant saving to the lining cost) there would have to be a feasible construction method that would provide a watertight or near watertight tunnel, i.e. a continuous waterproofing layer for sequential tunnel excavation and construction. If testing can demonstrate that sprayed concrete could be sprayed on to a partially cured thin skinned liner with a sufficient bond then the following sequence could be proposed:

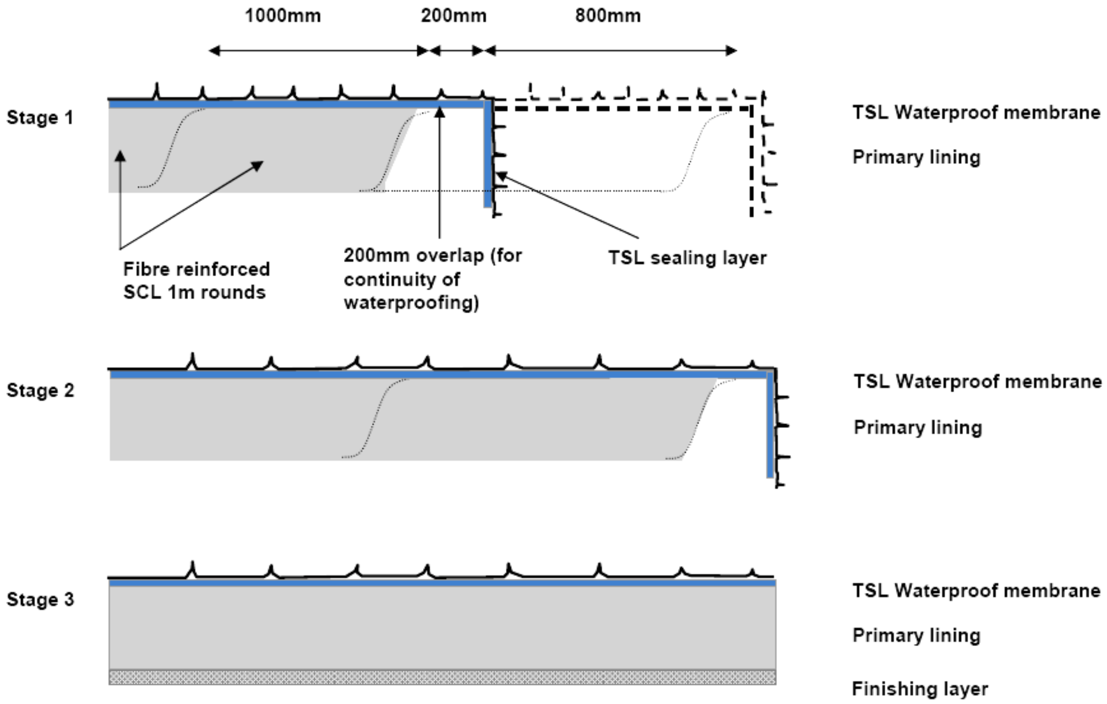


Figure 10: Practical application of SSL

Stage 1 and 2 show the proposed typical sequence of the single shell lining with the waterproof membrane sprayed against the excavated surface and acting as the sealing layer. The major difference with this methodology is that a 200 mm overlap is left to ensure that there is continuity in waterproofing between the 1 m rounds. Stage 3 indicates an application of a finishing layer.

For a typical 6 m diameter tunnel, Stage 1 based on typical construction rates could be broken down to the timeline shown in Table 1.

Table 1: Typical sequence for a 6 m diameter SSL tunnel (1 excavation round)

	Tunnel construction stage/ description	**Duration/ Minutes**	**Total time/ minutes**	**Thin skin liner age (tunnel shell) / minutes**
1	Excavate and muck one meter tunnel excavation round			
2	Spray thin skin liner sealing layer for tunnel circumference	10 – 15	10 – 15	
3	Spray thin skin liner sealing layer over tunnel face	5 – 10	15 – 25	10 – 15
4	Clean up and move out sprayer kit	5 – 10	20 – 35	15 – 25
5	Set up SCL spraying robot	5 – 10	25 – 45	20 - 35
6	Spray structural SCL layer			Approx. 30

Therefore the minimum curing time for the membrane / sealing layer unless construction is paused would be something in the order of 30 minutes.

Following discussion with BASF, it was proposed to carry out some initial testing of spraying a thin skin liner onto excavated material and to spray some test panels to check this method of construction is feasible and also provides structural bond requirements between the thin skin liner and the sprayed concrete, described in section 5.1.

5.1 Testing

5.1.1 A shaft construction site in London, June 2011

With the kind assistance of BASF, client and the contractor, trials were carried out at the SCL shaft construction site in London on June 2011 in order to establish the effectiveness of spraying Meyco TSL 865 directly onto London Clay.

The test was conducted at the bottom of an existing shaft on freshly excavated material beneath the over hang of the sprayed concrete shaft lining. The ambient temperature during the trial was between 13 and 15 degrees. The surface on to which the TSL was sprayed consisted of London Clay which had been excavated using a bucket with teeth. No dressing of the teeth marks had taken place.

Figure 11: Substrate prior to application on London Clay

Figure 12: Surface after application of TSL on London Clay

The surface was good enough to be sprayed onto without additional preparation. For rougher surfaces, applying a 25 mm smoothing mortar might be required. The TSL cured well and was successfully sprayed over with sprayed concrete.

5.1.2 Hagerbach test panels, July 2011

Encouraged by the success of the initial trial, more testing was proposed to test the capability of both Masterseal 345 (sprayed membrane) and MEYCO TSL 865 (thin skin liner) for early strength and bonding to freshly sprayed concrete at early curing ages.

Figure 13: Spraying TSL Meyco 865 onto a test panel, Hagerbach

3 test panels were prepared at the Hagerbach testing area in Switzerland:

a) A layer of Masterseal 345, measuring 4 mm thick was sprayed onto test panel 1 with a dry sprayed concrete mix sprayed onto the membrane after it had cured for just over 30 minutes.

b) A layer of Meyco TSL 865, measuring 5 mm thick was sprayed onto test panel 2 with a dry sprayed concrete mix sprayed onto the membrane after it had cured for just under 30 minutes.

c) A layer of Masterseal 345 (accelerated), measuring 4 mm thick, was sprayed onto test panel 3 with a dry sprayed concrete mix sprayed onto the membrane after it had cured for just under 20 minutes.

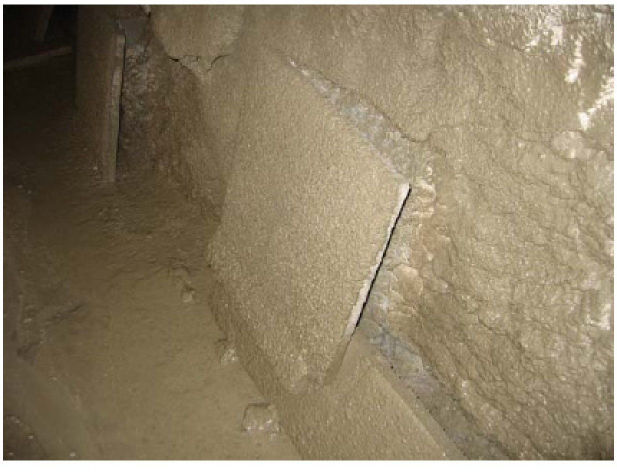
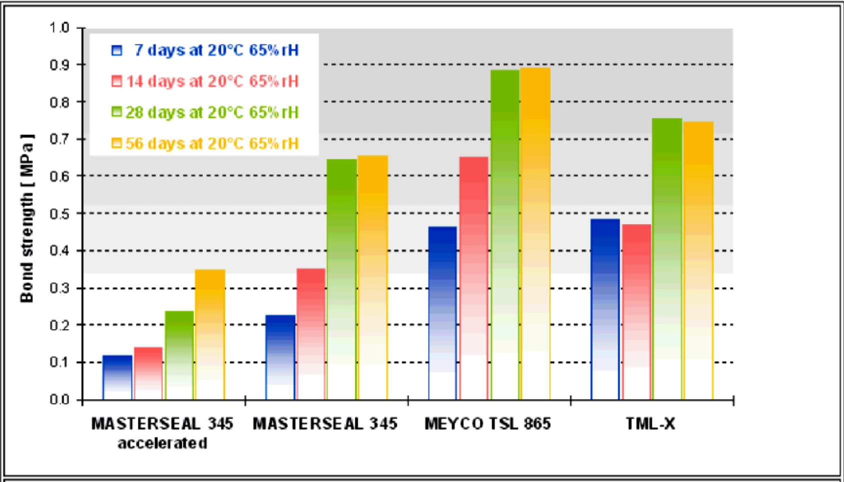


Figure 14: Test panel: Sprayed concrete onto 30 minutes cured TSL Meyco 865

5.2 Results

From the 3 test panels at Hagerbach the following results for Bond Strength were obtained:



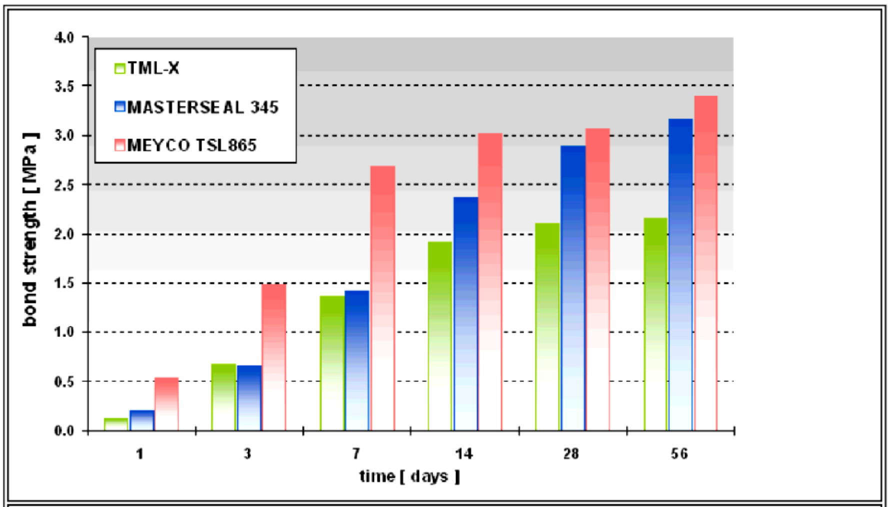
Spraying trails Hagerbach 14.07.2011
Bond strength according to ASTM D 4541-2 - Pull-Off Strength of Coatings Using Portable Adhesion Testers
after **56 days** at 20°C 65%rH

Figure 15: Bond strength vs. age from Hagerbach trial

The tests showed that good bond strength can be achieved with spraying concrete onto relatively young sprayed membrane, particularly the Meyco TSL 865 (see Figure 15). The latter could be classified as a "medium" strength TSL, according to Yilmaz's groupings [10]. While further testing would be required to prove that this could be achieved on a regular basis, this opens up the possibility for a single shell tunnel lining with sprayed membrane/sealing layer or mortar followed by a sprayed membrane and then the sprayed concrete structural lining.

5.3 Discussion

The trials carried out on site spraying the TSL 865 onto London Clay demonstrated that a single shell should be considered successful, and that a progressively strengthening bond was achieved between the TSL and the London Clay even though the conditions were not conducive to rapid curing.



Bond strength according to ASTM D 4541-2 - Pull-Off Strength of Coatings Using Portable Adhesion Testers
at 20°C 65%rH

Figure 16: Bond strength vs. age under laboratory conditions

The testing carried out at Hagerbach demonstrated that a bond can be achieved between the waterproof membrane and the sprayed concrete after a minimum curing time of the water-proofing membrane of 30 minutes. In comparison with what can be achieved under laboratory conditions as shown in Figure 16 it is clear that further optimization of this process is possible and further testing of this process should be carried out in particularly to determine:

- Optimal curing time of the thin skin liner to achieve a acceptable bond strength to the sprayed concrete compared to construction sequence requirements
- How accelerators effect curing time of the thin skin line compared to bond strength achieved with the sprayed concrete
- Whether an alternative product could be developed that could be optimized to fulfill both the sealing layer and waterproofing properties

6. Conclusion

For soft ground tunnels, the traditional approach of a temporary primary sprayed concrete lining is very wasteful and, with current technology, unnecessarily conservative. Over the last fifteen years a series of pioneering projects in the UK has revolutionized the design and construction of sprayed concrete linings. There is a growing acceptance of the use of sprayed concrete as permanent works as well as spray-applied waterproofing membranes. In turn this has generated a body of experience on real projects which has been fed back into the design methods and technology. While composite permanent sprayed concrete linings may not be suitable for all cases, there are many where this approach is very effective. Table 2 illustrates how the lining thickness could be reduced by using spray-on membranes and the composite action of all parts of the lining. As noted before, some key design assumptions limit the savings in materials for CSLs, although there are still significant savings in the costs of formwork and the time to install. The biggest savings are offered by using the SSL option. Some design issues remain and our company is involved in ongoing research in the field of fully composite linings.

*Table 2: Possible lining thicknesses for different lining options **

Lining option	Sealing layer	Primary lining	Secondary lining	Total
DSL	75 mm	325 mm	350 mm inside a sheet membrane	750 mm
CSL – no bond	75 mm	325 mm	300 mm inside a spray-on membrane	700 mm
CSL - bonded	75 mm	325 mm	250 mm inside a spray-on membrane	650 mm

* this refers to a large diameter, shallow tunnel in soft ground

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