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Where Are We Now with Sprayed Concrete Lining in Tunnels?

By Andrew Pickett and Dr. Alun Thomas

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 in-situ 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. Mott MacDonald is now providing design solutions for the use of permanent sprayed concrete with a variety of waterproofing solutions through its involvement as designers on major projects in the UK—in particular, soft ground tunneling, 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.

The focus of study has been on the last case in recent projects and, 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.

Initial findings will also be reported 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 modeling from a live project, will outline where 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.

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 (refer to Fig. 1[1]). The SCL options can be broadly categorized into three types. Double shell linings (DSL) involve a sacrificial primary lining, which takes the temporary loads, and a secondary lining to take the permanent loads (refer to Fig. 2). This has significant pedigree, however, because the primary is considered temporary while the secondary is designed to take both long-term ground loads and hydrostatic, thereby providing a robust design. It is a lot thicker than CSL types.[2]

Composite shell linings (CSL) involve the primary lining taking the temporary loads and a proportion of the permanent load through composite action with the secondary lining. Single shell linings (SSL) are one lining taking 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).

Composite Shell Linings

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 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 essential 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.

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

- 100% ground and hydrostatic loads applied to primary lining in the short term;
- The option of load sharing for the ground loads in the long term;
- Full hydrostatic load applied to secondary lining in the long term; and
- 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 DSL, 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

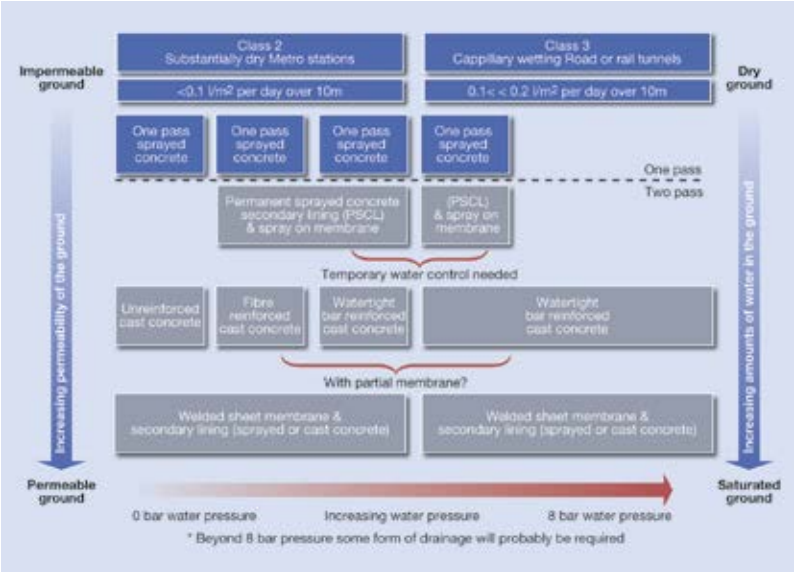

Fig. 1: Design options for linings and waterproofing[1]

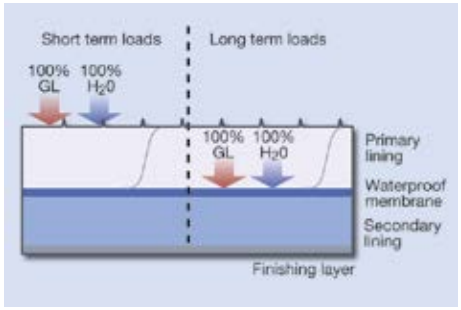

Fig. 2: Typical double shell lining

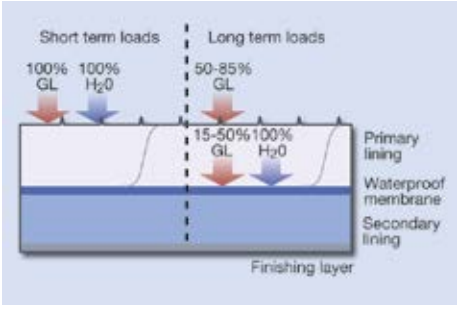

Fig. 3: Typical composite shell lining (partial composite with no shear or adhesive bond)

it varies depending on the loading behavior of the ground. In materials such as clay, there is a distinct short- and long-term behavior, 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 behavior 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 (3 in.) 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 as discussed later, and as shown in Fig. 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 shows 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 (145 psi); and
- Shear strength on membrane interfaces to be 2 MPa (290 psi).

The advantage, as discussed above, is the reduction to secondary lining thickness without compromising the water tightness 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 51,[4,5] and the design for Hindhead considered both load cases—with and without full composite action.

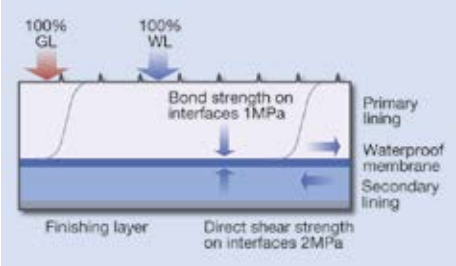

Fig. 4: Fully composite shell lining

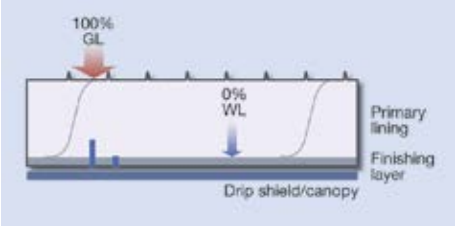

Fig. 5: Typical single shell lining

Single Shell Linings

Single shell linings (SSLs) 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 (refer to Fig. 5). SSLs have been widely used in the hydropower sector and in all tunneling sectors in certain countries, most notably Norway:

- No waterproofing membrane;
- Ground loading all on primary lining;
- No hydrostatic load;
- Watertight concrete design, but allows local seepage; and
- 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 SSL. That said, this can still remain as a design option for non-public tunnels where lower levels of water tightness are acceptable.

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 remove 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 fiber reinforcement (SFR) 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 as follows:

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 2 to 3 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 fiber reinforcement. The structural fibers are to increase the ductility of the concrete and provide toughness and post-crack resistance in the long term (see Reinforcement section). Conventional bar reinforcement is only required at openings and some headwalls. Smaller diameter bars (typically less than 12 mm [0.5 in.]) can be encased fully in sprayed concrete without too much difficulty. Larger bars (up to 25 mm [1 in.]) 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 fiber 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 (3 in.), 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 [4600 psi]), but measured at 90 days. The same concrete should achieve 28 N/mm² (4000 psi) 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, and the high strength introduces a new set of problems related to brittleness and underperformance of the fibers.

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 Improvements section);
- 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; and
- 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 modeling 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.

Analyzing the effects of composite action is more complicated than it might appear at first sight, since in cases of uneven loading the behavior 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.[9] Even under a relatively extreme combination of horizontal and vertical loads on a tunnel lining, no debonding in the normal direction was found, so this suggests 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

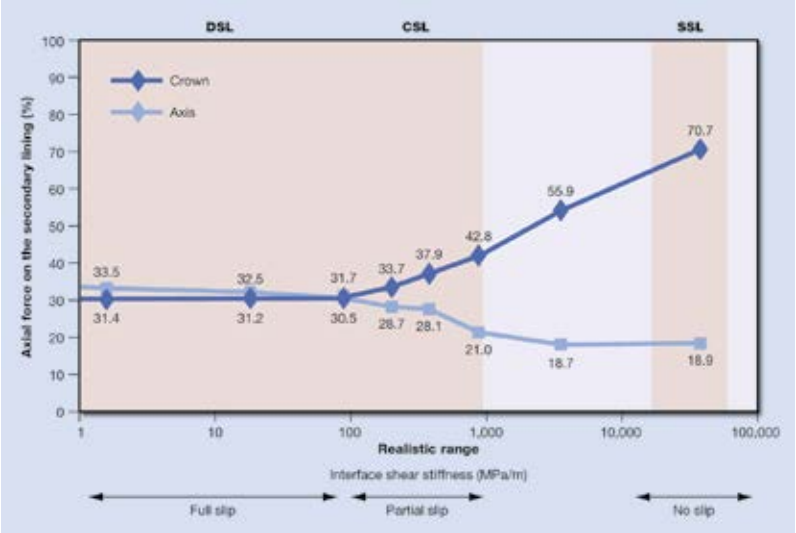

Fig. 6: The hoop load in a secondary lining vs the shear stiffness of the interface with the primary lining[9]

carried by the secondary lining varies from 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 fiber-reinforced sprayed. 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 fibers in order to limit explosive spalling and maintain structural integrity. The quantity of fibers 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 fibers in high-strength, low-permeability concrete mixtures significantly reduces the risk of explosive spalling when exposed to severe hydrocarbon fires.

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.

Reinforcement—Reinforcement of the linings will be provided by structural fibers in the sprayed concrete matrix in combination with steel bar reinforcement located around junctions and openings. Fibers—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 RILEM[8] and shown in Fig. 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, Design approach 1 was used and no benefit from the fibers was assumed. Clearly this is incorrect and unduly conservative. In Design approach 2, the fibers 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 Design approach 3, in which a simplified stress block, with a value of 0.37 fctm.fl, is used, based on RILEM.[8] This is conservative itself, because 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 (3 in.) beam test are higher than this at a deflection of 2 mm (0.08 in.).

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 fibers 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 RILEM[8]) but naturally, because this is a new material, the spacing and development of cracks within fiber-reinforced concrete is not as well understood as in conventional bar reinforced concrete.

In the past, specifications have often prescribed a dosage of fibers; for example, in permanent linings, typically 30 to 40 kg/m^3 (50 to 67 lb/yd^3) of steel fibers. 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

This 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 mm (0.1 in.) on the standard beam test. EN 144876 offers another alternative:

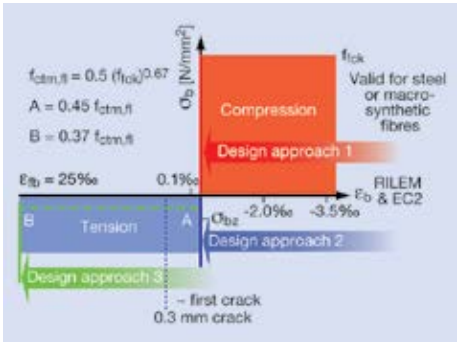

Fig. 7: Simplified stress-strain models for fiber reinforced concrete

C28/35 S 1.7 D 3.0

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

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 fibers. 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 fibers and creep for macro-synthetic fibers—deserves to be examined in detail dispassionately. Macro-synthetic fibers 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 fibers 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.

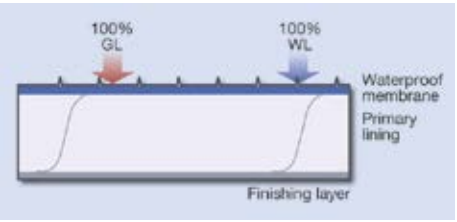

Fig. 8: Single shell lining with waterproof membrane

Improvements

An obvious first improvement would be to use the bond strength of the spray-applied membrane in a fully composite shell lining (refer to Fig. 4). As discussed earlier, this would lead 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. Only a modest bond is required for full composite action and the performance of a product can be verified by simple tests.

The real Achilles heel of composite shell linings remains the position of the waterproofing layer, which is more or less in the center 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. In turn, this leads to the conclusion 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 (refer to Fig. 8).

This has the advantage that it fulfills client requirements for a waterproof tunnel and reduces the overall lining thickness as per the conventional SSL. The salient features are:

- Application of a waterproof membrane that also has ground support properties to provide safe entry to face and 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; and
- 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 "Superskin" products, such as Masterseal 865 or Tamseal, could fulfill 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 defense against water ingress. This technology has been around since the 1990s and has been trialed 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 (0.2 in.) of "medium" strength TSL is equivalent to 50 mm (2 in.) 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 the 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.

Table 1: Typical sequence for a 6m 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 metre 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

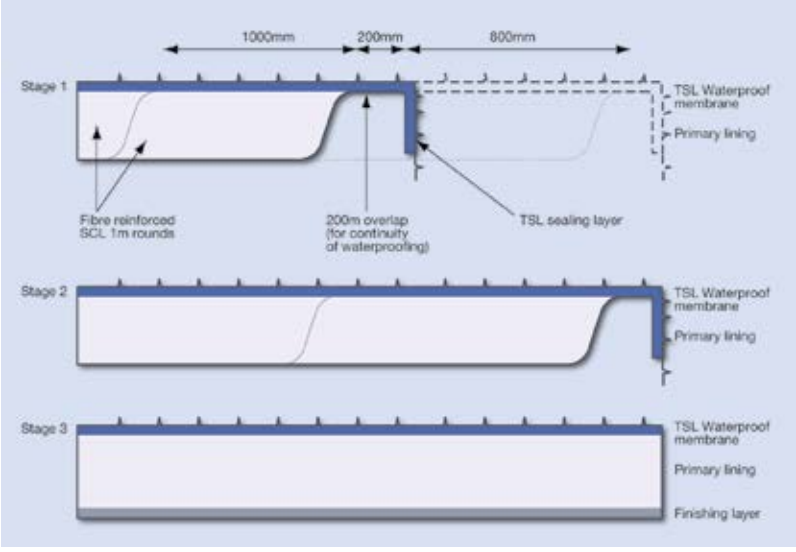

Fig. 9: Practical application of SSL

Single Shell Lining—A Practical Application

For a single shell lining, as described previously, 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:

Stages 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 (8 in.) overlap is left to ensure that there is continuity in waterproofing between the 1 m (3.3 ft) rounds. Stage 3 indicates an application of a finishing layer. For a typical 6 m (19.7 ft) diameter tunnel, Stage 1, based on typical construction rates, could be broken down to the timeline shown in Table 1.

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

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

spraying a thin skin liner onto excavated material and to spray some test panels to check that this method of construction is feasible and also provides structural bond requirements between the thin skin liner and the sprayed concrete, described next.

Testing

A shaft construction site in London, June 2011—With the assistance of BASF, the client, and the contractor, trials were carried out at the SCL shaft construction site in London in 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 overhang of the sprayed concrete shaft lining. The ambient temperature during the trial was between 13 and 15°C (55 and 59°F). The surface onto 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.

The surface was good enough to be sprayed onto without additional preparation. For rougher surfaces, applying a 25 mm (1 in.) smoothing mortar might be required. The TSL cured well and was successfully sprayed over with sprayed concrete.

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.

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

a) A layer of Masterseal 345, measuring 4 mm (0.15 in.) 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 (0.2 in.) thick was sprayed onto Test Panel 2 with a dry sprayed concrete mix sprayed

"For soft ground tunnels, the traditional approach of a temporary primary sprayed concrete lining is very wasteful and, with current technology, unnecessarily conservative"

*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	750mm
CSL-no bond	75 mm	325 mm	300 mm inside a spray-on membrane	700mm
CSL-bonded	75 mm	325 mm	250 mm inside a spray-on membrane	650mm

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

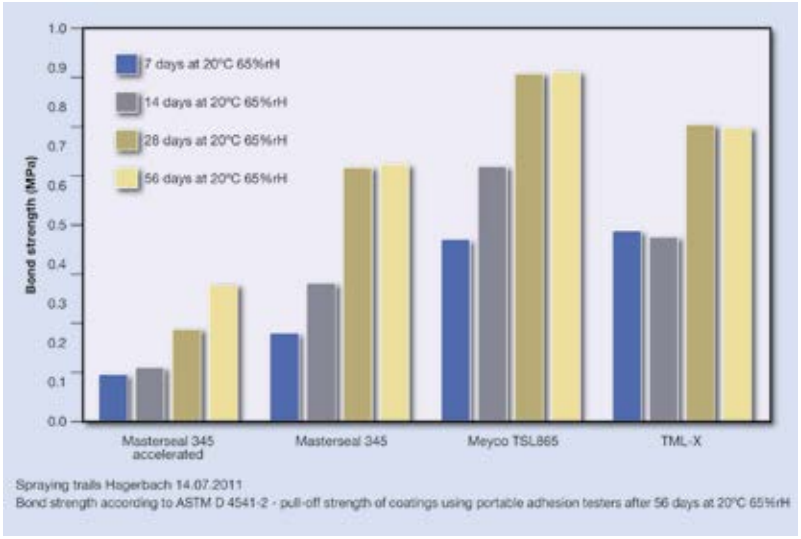

Fig. 10: Bond strength vs. age from Hagerbach trial

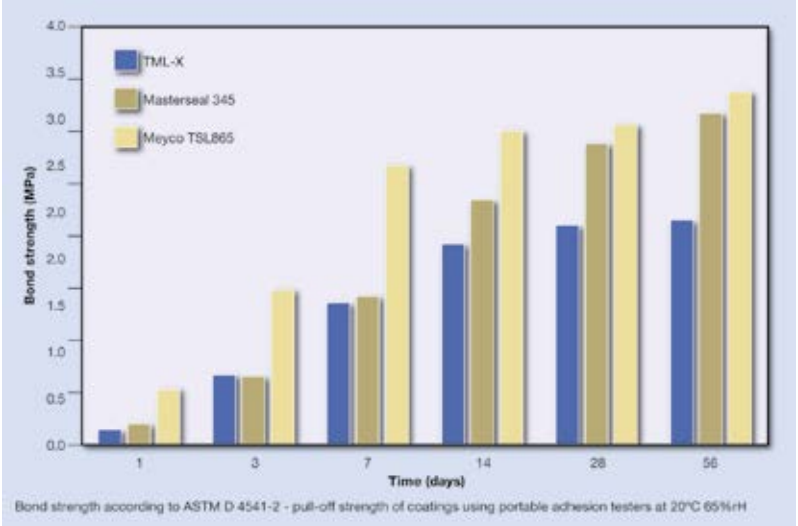

Fig. 11: Bond strength vs. age under laboratory conditions

onto the membrane after it had cured for just under 30 minutes; and

c) A layer of Masterseal 345 (accelerated), measuring 4 mm (0.15 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.

Results—From the three test panels at Hagerbach, the following results for bond strength were obtained:

The tests showed that good bond strength can be achieved with spraying concrete onto relatively young sprayed membrane, particularly the Meyco TSL 865 (refer to Fig. 10). 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.

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.

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 waterproofing membrane of 30 minutes. In comparison with what can be achieved under laboratory conditions, as shown in Figure 11, it is clear that further optimization of this process is possible, and further testing of this process should be carried out in particular to determine:

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

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 15 years, a series of pioneering projects in the UK has revo-

lutionized 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 Mott MacDonald is involved in ongoing research in the field of fully composite linings.

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