PERMANENT SPRAYED CONCRETE LININGS – AN INTERNATIONAL UPDATE

DAUERHAFTE SPRITZBETON INNENSCHALEN – EINE BETRACHTUNG DER INTERNATIONALEN LAGE

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The objective of this paper is to give infrastructure owners and their advisors the confidence to incorporate permanent sprayed concrete linings into their underground space design. Despite being used for many years in certain countries it is still not universally accepted. Inspired by this challenge, an ITA working group collected international experience and collated the gained know-how in a new publication. Their main findings and considerations, as well as some detailed case histories to support their arguments, are dealt with in this paper.

Spritzbeton als dauerhafter Baustoff für Tunnelinnenschalen wird derzeit weltweit sehr zurückhaltend eingesetzt, trotz seiner offensichtlichen vielen Vorteile vor allem in variablen Geometrien. Dieser Artikel handelt von vier bereits vor Jahren ausgeführten Projekten und wie sie sich heute darstellen. Zusätzlich wird auf die jüngste ITA Publikation über dauerhafte Spritzbetonschalen eingegangen, auch auf Gemeinsamkeiten mit den untersuchten Projekten.

1. Introduction

Everybody can agree that urbanization is a global trend, with more than 50 % of the global population already living in cities. It is also understood that public transport, and in particular metro systems, are the only way to deal with the enormous volumes of traffic. The hundreds of metro stations already built, or to be built soon, form underground labyrinths. The complex and continually varying geometries of these underground systems demand versatile and permanent lining solutions, which sprayed concrete can offer. An ITA internal study in 2017 has revealed that more than 1500 km of tunnels have already been built with permanent sprayed concrete linings (PSCL), mainly in Northern Europe and Australia [1]. Despite this proven track record, the merits of permanent sprayed concrete linings are surprisingly not universally recognized, and awareness of this technology is patchy. Hence sprayed concrete as permanent support is not being used as widely as it could be.

Why is this the case? Isn't sprayed concrete just a concrete, typically with a higher cement content, placed pneumatically instead of being cast as standard concrete is? Why isn't this concrete accepted worldwide as permanent support? All too often it is used only as temporary support, with an assumption that it wastes away over time. If it doesn't - as a lot of evidence suggests - isn't it then a waste of money and resources, producing unnecessary amounts of greenhouse gas emissions?

There are many more reasons why our industry should really consider using sprayed concrete as permanent support more often. The following text will deal with considerations and case studies to support the use of sprayed concrete as a valuable and versatile support means. This paper is in part based on the recently published ITA WG12 / ITAtech report, *Permanent Sprayed Concrete Linings* [1].

In the following section, some general design considerations will be explored, followed by brief descriptions of some case studies. These projects chart the development of this technology from its initial use in rock tunnels, for repair work and non-public tunnels, through to infrastructure tunnels in rock and now to public underground spaces in soft ground. This will illustrate both the versatility and technical merits of this technology.

2. Design considerations

Sprayed concrete contains the same raw materials as conventional concrete, is spray-applied and (in the wet system) has an accelerator added so that it adheres to the wall. It contains smaller aggregates than standard concrete and a higher proportion of cement, which influences its durability, shrinkage and creep. It is also said that sprayed concrete, in contrast to conventional cast concrete, is loaded immediately after being placed. But this is true only in soft ground or weak rock, where the sprayed concrete is used as primary support. In hard rock, or when used as an inner lining, sprayed concrete is loaded in the same way as a cast concrete shell would be [1].

It appears that the main obstacles to the wider use of PCSL are personal mindset, a potential mistrust of the application quality and - potentially - a lack of codes and standards. It is clear that much long-standing experience is based on dry-mix applied sprayed concrete which can sometimes lead to doubtful quality.

This paper lists some cases where PCSL were used some time ago and records how they look today (Table 1). Additionally, some cross references will be made to considerations outlined in the recent ITA publication [1].

Tab.1: Examples of PSCL projects

	Project	**Country**	**Type**	**Ground**
1	Hirtenberg	Austria	Storage caverns	Rock
2	Giswil	Switzerland	Emergency access	Soil / Rock
3	Gevingås	Norway	Rail	Rock
4	Crossrail	UK	Rail	Soft ground

3. Hirtenberg, underground storage caverns

3.1 Refurbishment works in 2008 [2]

The company Hirtenberger Defense Systems in Austria operates underground storage caverns of various lengths and cross sections (Figure 1). These caverns, originally lined with sprayed concrete, were out of use due to too much water ingress. It was decided to refurbish them with a spray-applied waterproofing membrane and a 150 mm-thick, fiber-reinforced, PCSL (C25/30/J2/XC4/XAT/GK8). This work was undertaken in 2008. Figure 2 shows a cavern before the application of the sprayed membrane, Figure 3 the sprayed concrete application and Table 2 the mix design.

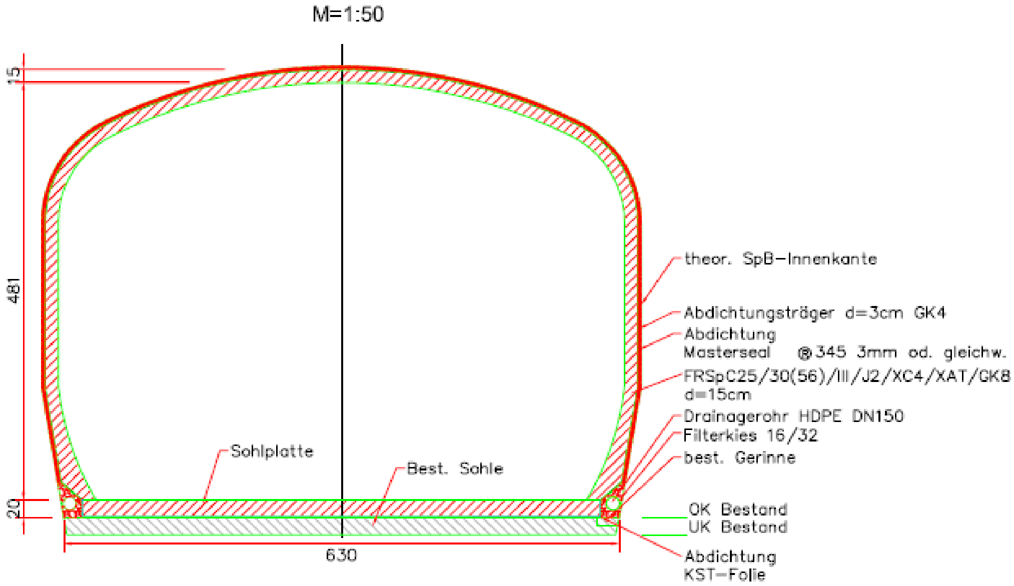

Figure 1: Typical cross section and proposed refurbishment measures [iC]

Figure 2: Substrate prepared to receive the sprayed membrane. Dripping water channeled via stripes into invert. Depth guidance pins installed for the thickness control of permanent sprayed concrete [Master Builders Solutions]

Tab. 2: Mix design for the wet-mix application

Component	**Quantity for 1 m³**
Cement CEM I R HS C_3A-free	450 kg
Water	192 l (w/c = 0.43)
Aggregates 0-4 mm	1230 kg
Aggregates 4-8 mm	410 kg
Plasticizer and air entrainer	3.15 kg + 0.38 kg
Steel fiber	35 kg
Polypropylene microfibers	1.2 kg
Target spread flow-table test according EN 12350-5	*560-620 mm*
Concrete temperature delivered	*20-22 °C*

The cement content in this low heat CEM I mix was increased to 450 kg/m³ to achieve, in combination with the rather low water-cement (w/c) ratio (for Austria), a better reactivity with the alkali-free accelerator which was added later.

The refurbishment was completed in 2008 and the caverns are now used as a storage facility, as intended.

Figure 3: Application of the final sprayed concrete layer [Master Builders Solutions]

3.2 Inspection in summer 2020 [3]

In September 2020 a site inspection was executed to assess the quality of the PCSL applied in 2008.

The following general observations were made:

- All caverns looked dry, only two spots with some minor water ingress were found
- The sprayed concrete was mostly uncracked; a few circumferential cracks were visible
- The circumferential cracks didn't correspond with anything (e.g. high points of the slightly undulating support layer)

The climate conditions underground:

- In Cavern 1 the climate is controlled at 13-15 °C and 60-65 % relative humidity (rh) for storage reasons
- In all other caverns the naturally constant temperature is about 10 °C with 80 % rh throughout the year
- A very gentle ventilation system provides a fresh air supply

Detailed observations:

- Cavern 1 (controlled climate) has
  - Three circumferential, rather straight cracks with mouth openings of up to 2-3 mm
  - The two wet spots correspond with the circumferential cracks, see Figure 4
  - The horizontal distance in between the three cracks is about 5 and 20 m respectively

- Cavern 2 (10 °C, 80 %rh)
  - Two circumferential cracks with lesser crack mouth openings than those in Cavern 1 and no wet spots (completely dry)
  - The cracks are showing a gentle zig-zag pattern and are not necessarily connected to each other but look like a single crack system
- All other caverns (10 °C, 80 %rh) are
  - Completely dry and display a few cracks running from the invert up to about 1 m height, see also Figure 5.

Figure 4: Crack and wet spot in Cavern 1 [Master Builders Solutions]

Figure 5: Crack from invert upwards (here Cavern 3) [Master Builders Solutions]

3.3 Considerations and conclusions

PCSL was used for the cavern refurbishment and clearly did the job. The cavern linings show very few cracks considering the several hundred meters over which it was used. All the discovered cracks are vertically oriented which indicates horizontal shrinkage.

Since the cavern system was built many years ago and the original lining was kept in place, it can be assumed that the freshly-applied sprayed concrete lining is unloaded or only lightly loaded. Therefore, it can also be assumed that there were never any horizontal or inclined cracks that were later closed by compression.

Overall, the stable and rather humid climate was, and is, favorable for the long-term hardening of the concrete and its durability. It is also notable that the climate-regulated cavern has the most cracks (three in total) with the widest crack mouth openings. The caverns further into the mountain, receiving the least fresh air, have the fewest and shortest cracks.

The concrete temperature when it was applied was in a favorable range, and the cement used developed less heat compared to standard cements, which in combination helped to eliminate temperature-related cracking. The rather high humidity, in combination with the very gentle ventilation, allowed - and still allows - a good and proper long-term curing of the spray-applied concrete layer. Since the few cracks have hardly opened, fibers crossing them couldn't be assessed, but it is assumed that they contributed positively to the overall behavior and act as additional safety measure.

4. Giswil, emergency escape tunnel

4.1 Construction of the Giswil escape tunnel in Switzerland [4]

In 2003/2004 the escape tunnel was excavated by a 4 m-diameter hard-rock TBM, parallel to the double-lane road tunnel. The first few meters at either end were excavated by drill and blast. It was decided to employ a sprayed primary lining in combination with spray-applied waterproofing in the first 200 m from the entrance, with the invert waterproofed by a sheet membrane. The final inner lining was designed to be a steel fiber-reinforced, 100 mm-thick, wet-sprayed concrete (Figure 6), covered with a thin sprayed concrete coating without fibers. The mix design included 450 kg/m³ cement and a w/c ratio below 0.5. The accelerator dosage enabled a lower J2 strength development.

Figure 6: Wet-mix sprayed concrete application [Master Builders Solutions]

4.2 Inspection in autumn 2020 [5]

The tunnel was re-visited in October 2020 to visually evaluate the lining behavior. The following observations were made:

- The tunnel entrance doors were closed, allowing no natural ventilation
- The temperature in the tunnel was about 12° Celsius with about 60 % rh
- The tunnel lining looked dry and intact (Figure 7), with four small, slightly damp patches
- Two of the three installed manometers showed about 4 bar pressure, while the other indicated no water pressure. The reliability of the manometers can be questioned 16 years after installation, though dripping water at one of the manometer locations suggested water pressure (Figure 8)
- About five long cracks were found in the 200 m long stretch, mostly vertically oriented, with a crack mouth opening of about 0.2-0.3 mm
- The longest crack was about 3 m long, crossing the central crown area in a zig-zag pattern
- A very few short cracks were also found, with an average length of about 200 mm (Figure 9)
- In some cracks, about 100 mm were sintered, indicating a deficiency of the system waterproofing for a short time.

Figure 7: Tunnel as inspected 2020 [Master Builders Solutions]

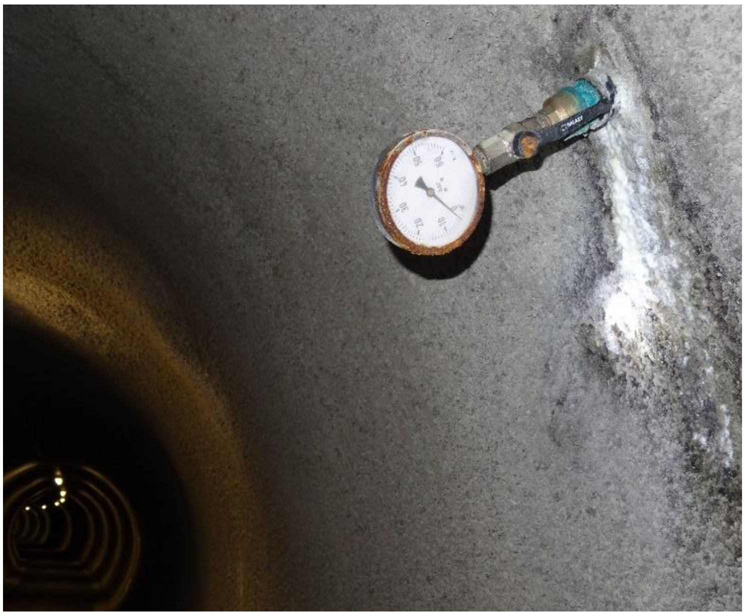

Figure 8: Manometer indicating 4 bar water pressure [Master Builders Solutions]

Figure 9: Small, short vertical crack [Master Builders Solutions]

4.3 Considerations and conclusions

The TBM-excavated rock tunnel has a PCSL with a spray-applied waterproofing layer in a sandwich construction. It can be assumed that the lining in the nicely-shaped rock tunnel (except for the first few meters at the portal, where soil was encountered) was barely loaded by the ground but potentially received a load from water pressure. The sprayed concrete was applied by qualified personnel and the acceleration not overdone, which means that no unnecessary heat development was provoked. Since the application took place in autumn, temperatures were quite pleasant and favorable. Curing was not considered, but the higher humidity in autumn, in combination with natural ventilation, only provided some sort of curing.

The few cracks observed run mostly vertically, indicating some horizontal shrinkage, but only have very small crack mouth openings. Most of the cracks look completely dry; some millimeters with sintered material indicate that there was some water, potentially under some pressure as also indicated by two of the three manometers. Whether the water pressure is high enough to have closed the cracks over time can’t be assessed, as there was no indication of longer or completely closed cracks.

Fibers crossing the cracks couldn’t be identified, since the crack mouth openings are very limited. But it is generally believed that it is beneficial to use structural fibers in a PCSL.

Overall, it can be said that qualified personnel applied a good mix, and that autumn was a good time in this case to apply sprayed concrete because the temperatures and humidity giving the concrete layers more time and moisture to cure properly. The PCSL was definitely the right choice.

5. Gevingås rail tunnel, Norway

The 4.1 km-long single-track Gevingås rail tunnel (68 m^2) is located 25 km north of Trondheim on the Nordland rail line which connects Trondheim with Bodø. The tunnel was constructed between 2009 and 2011 by the drill and blast method to shorten and modernize an old part of the Nordland rail line, constructed in the 1880s. The geology encountered is outlined in Table 3.

Tab.3: Ground conditions

Hard rock, meta-sediments – meta turbidites with conglomerate, sand- clay- and siltstone origin		
Uniaxial compressive strength intact rock	110-150 MPa	Mean 124 MPa
Young’s modulus intact rock	40-54 GPa	Mean 46 GPa
Moderately to densely jointed rock mass		
Fair rock mass quality	Prevailing Q-values in the magnitude of 9	
Zones with poor rock	With Q-values in the magnitude of 1	

Permanent rock support was constructed with fiber-reinforced sprayed concrete and rock bolts. It was based on an engineering geology and functional assessment and verified against the support categories proposed by the Q-system.

The design of the final inner lining was originally based on the traditional Norwegian method using polyethylene (PE) foam sheets for thermal insulation and umbrella waterproofing, subsequently covered with fiber-reinforced sprayed concrete to protect the flammable PE foam sheets against fire.

This design was reconsidered during the construction phase, and an alternative innovative method was used. It consisted of a system with a spray-applied waterproofing membrane covered with a final inner layer of sprayed concrete, applied directly onto the membrane. Better technical performance and better maintainability, as well as lower predicted long-term maintenance costs, were the reasons for this design change.

The alternative lining system does not have any thermally insulating elements. Lack of experience with the system under freezing conditions was an issue. Therefore, the warmer central part of the tunnel, 1850 linear meters long, was selected for the new approach. The traditional PE foam sheet system, with thermal insulation properties was kept for approximately 1000 linear meters at either end of the tunnel. Near the portals a cast-in-place lining structure was constructed. A longitudinal section with the different lining constructions is shown in Figure 10. The two different lining systems for the main part of the tunnel are illustrated in cross section in Figure 11.

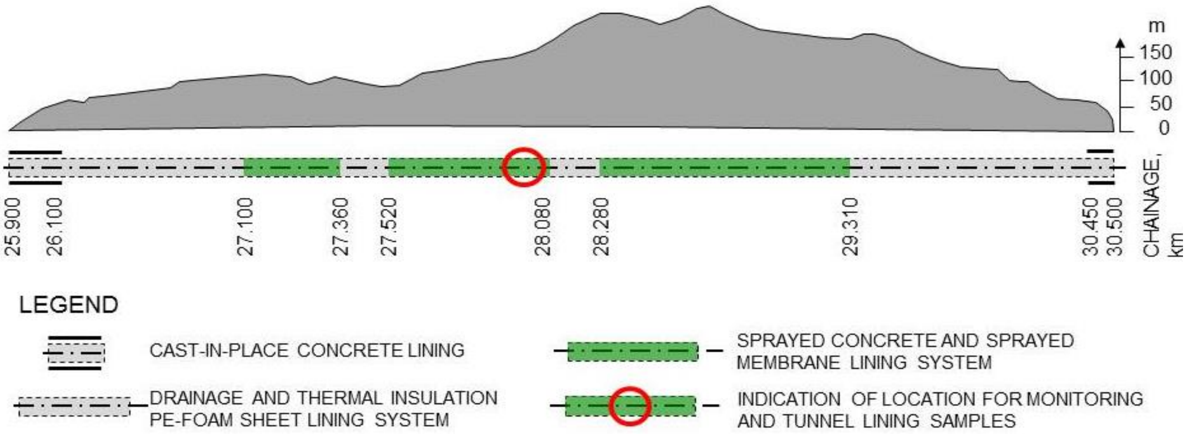

Figure 10: Longitudinal section of the Gevingås rail tunnel, total length 4100 m, showing the different constructed lining types [6]

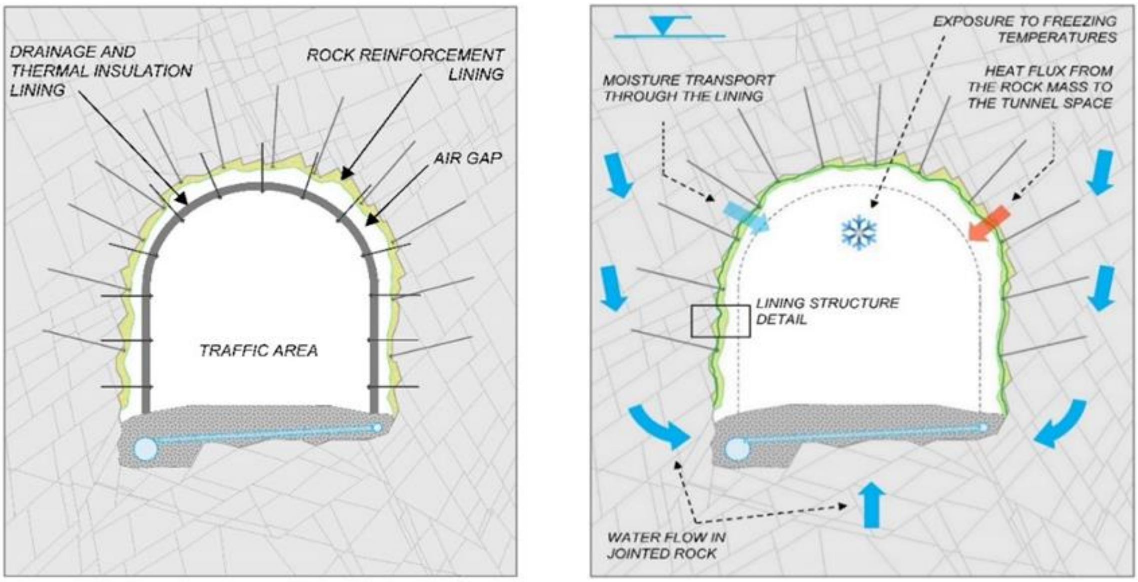

Figure 11: Cross sections of the final inner lining of the Gevingås rail tunnel. Left: Original design with the PE foam sheet drainage system, realized in 2200 m of the tunnel length. Right: the alternative and innovative design with sprayed concrete and spray-applied water-proofing in the final inner lining, realized in 1850 m of the tunnel length. The waterproof redirects the water flow as shown [7]

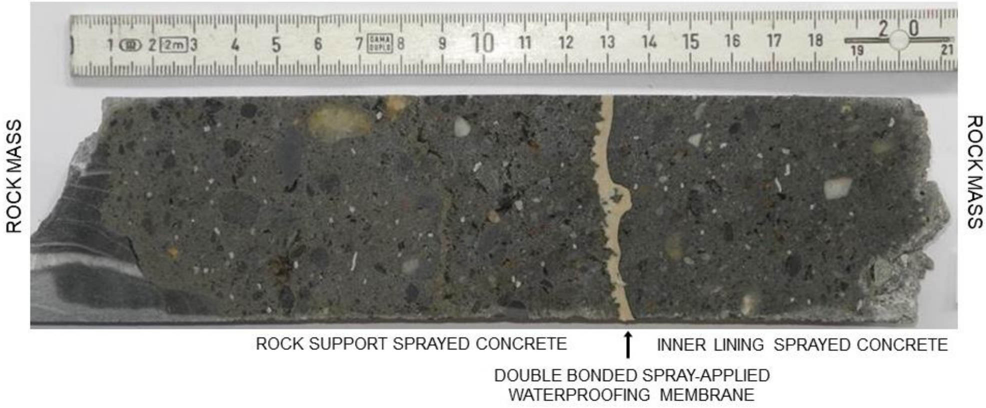

Figure 12: Drill core sample from the complete final waterproof lining [8], drill location shown in Figure 11 right (lining structure detail)

The alternative lining design, based on sprayed concrete and a spray-applied membrane, cost a similar amount to the original design to construct. The technical performance of the alternative design is considered more beneficial than the traditional lining system based on PE foam sheets. The main benefits are reduced maintenance over the planned service lifetime and having no flammable materials in the lining structure.

The condition of the lining after approximately nine years of operation are very favorable. The air temperature in the tunnel air ranges from -5 to + 15 °C in the section of the tunnel which has the PCSL. No freezing damage has been observed and no maintenance has been required. No occurrence of new water seepage has been recorded.

Figure 13: Gevingås rail tunnel. Left: interior of the tunnel showing a portion of the tunnel with a final inner lining of sprayed concrete and a spray-applied waterproofing membrane. Right: the northern portal with a cast-in-situ lining and showing the old rail line to the right [8]

6. Crossrail (The Elizabeth Line)

The extension of SCL tunneling from rock tunnels to soft ground is well-documented [9]. In a similar fashion PSCL was first applied in rock tunnels and is now seen increasingly often in soft ground projects. Since many cities stand on soft ground, and this is where the demand for complex underground spaces is highest, there is massive potential for the further use of PSCL.

In this context, the Crossrail project in the UK represents an important landmark in PSCL application. This is the first major metro project in a Western country in soft ground to adopt PSCL for many of the stations. The key features of the project are described below.

6.1 Project description

The Elizabeth Line is a new railway, passing East to West with an underground section through the heart of London. Formerly known as Crossrail, it is a vital link in the commuter rail network. The tunneling works were constructed from 2012 to 2017. PSCL is used widely on this project for a total of about 14 km of tunnels, most notably:

- All station tunnels and adits at Bond Street, Tottenham Court Road, Farringdon, Liverpool Street Station, and Whitechapel.
- All intermediate shafts, crossovers and cross passages (Stepney Green Crossover, Whitechapel Crossover, Eleanor Street, Mile End, and Limmo).

The geology at the levels of the tunnels is predominantly stiff, impermeable London clay. The depth of the tunnels varies up to about 40 m. Further information can be found at: learninglegacy.crossrail.co.uk

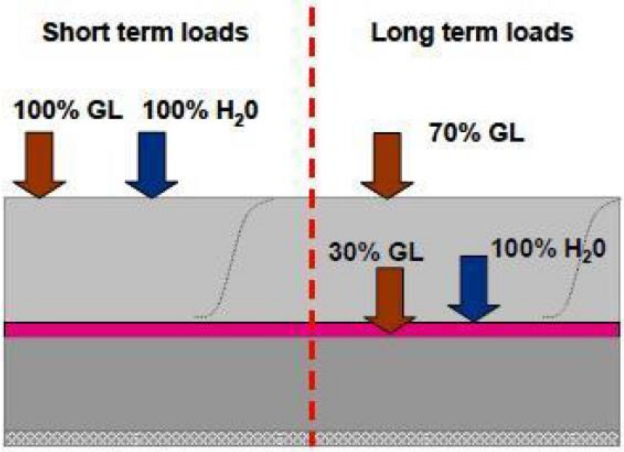

Figure 14: Load sharing between primary and secondary SCL linings [10]

6.2 Design Approach Adopted

The **permanent primary lining** was designed to take the full short-term applied ground load and any other loads, during the two years prior to secondary lining installation (see Figure 14). The primary lining consists of a sprayed concrete lining containing structural steel fibers, which increase the concrete's ductility and provide post-crack tensile resistance. The external 75 mm of the lining is considered to be sacrificial in the long term.

The **secondary lining** was designed for:

- Long-term water pressure
- Some long-term ground pressure (a portion of this was carried by the primary lining)
- Internal loads (mechanical and electrical equipment)
- Temperature and shrinkage

The secondary linings were designed to also contain micro-synthetic fibers (typically 1 kg/m^3) to limit explosive spalling and maintain structural integrity in case of a fire. Table 4 contains details of a typical mix design.

The specification for the concrete lining was C 32/40 with a flexural tensile strength of D1 S1.8 (after BS EN 14487-1). The lining thicknesses for a 10 m-diameter platform tunnel were typically 325 mm (excluding the sacrificial layer) for the primary lining and 400 mm for the secondary lining.

The design life is 120 years. Apart from the strength requirement and normal concrete mix design, other criteria included: a mean water penetration of less than 25 mm for the primary lining, shrinkage less than 0.03 % and a water-cement ratio less than 0.45.

A spray-applied waterproofing membrane was installed between the primary and secondary lining of all SCL tunnels (except Farringdon Station and other tunnels which are in the Lambeth Group, which contains sands and gravels), to provide a waterproof lining.

Junctions were designed so that, where bar reinforcement was required in the secondary lining, it could be installed safely within an enlarged section of the fiber-reinforced primary lining.

These were significant innovations at the time and enabled the elimination of almost all of the steel bar reinforcement in the linings. This was the first large-scale use of PSCL, and spray-applied waterproofing membranes on the London Underground. More details of the design can be found in [10].

Tab.4: Typical secondary lining mix design

Component	**Quantity for 1 m³**
Cement CEM I	419 kg
Microsilica	54 kg
Water	162 l (w/c = 0.39)
Marine sand	860 kg
Limestone aggregate	860 kg
Plasticizer	7 kg
Steel fibers	45 kg
Polypropylene microfibers	1 kg
Target spread flow-table test according EN 12350-5	*550 mm*

7. Site observations in relation to the recent ITA publication on Permanent Sprayed Concrete Linings [1]

The cases presented above can all be seen as successful uses of PCSL in technical terms. The sprayed concrete linings are performing as expected; the concrete exhibits only a few cracks, which are most likely related to shrinkage.

The ITA paper deals with some basic design considerations and potential consequences of mix design and application. However, the authors struggled, with reasonable effort, to get design and application information about the observed tunnels, with application details especially difficult to find. As a consequence, we had to partly work with assumptions for our comparison between theory and practice.

It can be assumed that at least two of the four inner lining shells are only lightly loaded (Hirtenberg, Gevingås); the other two could have experienced, and still may experience, a load increase over time. The reason for highlighting this difference is that it reinforces the assumption that loaded shells will experience less or no cracking due to shrinkage, whereas unloaded ones are more prone to do so.

The mix designs used were standard mix designs, as per local experience. With our knowledge of the country preferences, it can be said that none of the mix designs were over accelerated, neither were the delivered concrete temperatures too high. The internal heat development due to the acceleration was obviously limited and did not produce thermal cracking afterwards. Additionally, the visual observations also suggested a reasonably high quality of application, which correlates with the ITA recommendation that experienced and trained personnel should be used.

For three of the cases we have no evidence of any special efforts being made on systematic curing such as adding chemicals to the mixes, spraying chemicals or water onto the concrete after application or applying a water mist. We can observe that two cases had, and still have, very low or no ventilation (Hirtenberg, Giswil) and that Gevingås relies on natural ventilation. The Elizabeth Line is the exception, with some isolated curing attempts. In general, rather humid and stable climates supported good continuous hydration and the linings were therefore less prone to long-term shrinkage cracks. All four projects were constructed in Europe where the climate is potentially quite favorable. To get a more balanced view on this, further investigations should also include projects in hotter and dryer climates.

In summary, the mix designs for the PCSL used on the investigated projects were executed to a good local standard, the application was done by qualified personnel and the curing, though not a priority, was supported by the climatic conditions. The lining aesthetics and functionality after several years is as expected. This all correlates very well with the recommendations in the ITA publication.

8. Conclusions

PCSL offers a very versatile option for linings in tunnels, but acceptance of it varies for many reasons. The most recent ITA publication, *Permanent Sprayed Concrete Linings,* combined with the evidence of revisited jobs constructed years ago, suggest that more attention should be given to this lining option. But it should be noted that focus must be given to the mix design proposals, the application details and the qualification of the applicator to ensure good workmanship.

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