SPRAYED POLYMER WATERPROOFING MEMBRANES FOR SCL TUNNELS: A FUTURE DESIGNED FOR DRY

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1. INTRODUCTION

The use and acceptance of sprayed concrete in underground construction has been growing steadily. In the UK, there is a particular focus on the use of sprayed concrete for permanent primary and secondary linings in Spray Concrete Lined (SCL) tunnels, and not just as the temporary primary lining. The combination of using fibres for reinforcement and the use of improved construction methods such as the LaserShell™* system, is making this an attractive construction method.

The use of sprayed concrete for secondary linings however, can present challenges for traditional sheet waterproofing methods. In addition, with many urban underground construction projects requiring increasingly complex geometry, there is a requirement for waterproofing systems that can create the same flexibility in construction as sprayed concrete itself. Consequently, sprayed waterproofing membranes have been developed for underground use, in conjunction with sprayed concrete, over the last 10 years. Sprayed waterproofing membranes have been gaining acceptance in SCL tunnelling around the world, and this paper sets out the important considerations in using sprayed waterproofing membranes, what they are and are not capable of, and lessons learnt from previous projects, using the Buenos Aires Metro Line B extension as an example.

2. WHY A SPRAYED MEMBRANE?

Traditionally, SCL tunnels have been waterproofed using welded sheet systems. These are joined together using extensive seaming, and where the seams can be tested (automated double seaming) which is usually in tunnels of constant cross section, they can be effective. However, they can have drawbacks where the following conditions exist:

- Complex geometry means single welds are used that cannot be tested
- Where high waterproofing requirements exist – a "dry" tunnel is required
- Where sprayed concrete is to be used for the secondary lining

Any leaks in such systems are usually associated with seams, but because the membrane is not bonded to the concrete on either side of the membrane, leaks may circulate and show in areas distant from where the leak actually is – making leak fixing afterwards very difficult, expensive and sometimes impossible. There is an expectation in tunnelling that there will be some leakage, so it is commonplace to compartmentalise the waterproofing on the "dry side" of the membrane with water bars and grout tubes in preparation for leak sealing. A sprayed waterproofing membrane can be used to great effect in a complex geometry tunnel, such as a metro station project, because a sprayed membrane will be continuous (free from seams) once installed. Additionally, because the membrane is well-bonded on both sides - to the primary and secondary sprayed linings - water does not track between the membrane and the concrete linings. A membrane that is robust and fully bonded to the primary lining makes the use of sprayed concrete as the secondary lining much easier, because the sprayed concrete secondary lining will bond directly to the membrane surface.

3. DESIGNING FOR DRY

The expectation that tunnels will always leak is due to previous experience of waterproofing in the tunnelling environment. However, if the primary sources of leaks have been deleted – that of welded seams and lack of adhesion to concrete linings – then a dry tunnel should be achievable if we design within the capabilities of the waterproofing membrane. It is important therefore to understand what sprayed membranes are and are not capable of. As sprayed membrane technology first emerged in SCL tunnelling, there were many claims made of it. For example that it could be sprayed on "as shot" concrete and that it could provide a watertight seal to as shot concrete that was steel fibre reinforced. The reality is that sprayed waterproofing membranes are not new. They have been used effectively in all sorts of civil engineering application for the last 40 years or more. Those experienced in their use understand what is required to make them work

3.1. Substrate preparation

In other civil engineering and tunnelling applications where sprayed membranes have a long track record of success, surface preparation has always been seen as an important factor. This is quite simple, in that if applying a continuous membrane to a concrete surface, the surface must be continuous, free from voids or holes and free from protrusions that would stick through the membrane. The situation is no different in SCL tunnelling, except that in creating a substrate of sprayed concrete, we know that the surface will be relatively rough, may contain voids and shadow areas, and if using fibre reinforcement, will have fibres protruding from the surface. Whilst it is then attractive for a waterproofing manufacturer to say this can all be sprayed over without any problem, the reality is that the membrane will not be 100% watertight, as fibres and voids will create water leakage paths.

Where a sprayed membrane can be tested for integrity in situ, it can be demonstrated that spraying on as shot surfaces does not create a watertight membrane. Therefore, substrate preparation is necessary prior to application of a membrane. This is becoming widely accepted by those who have completed a number of projects, with Naylor et al of Mott MacDonald presenting at underground Construction 2011 in London (1), that projects going forward with sprayed membranes will require substrate preparation on sprayed concrete. Substrate preparation means creating a flatter surface than an as sprayed finish. This can be achieved in 2 different ways:

- Using a concrete render on the surface and finishing with a trowel as a separate activity
- Using a fibre free final pass on the sprayed concrete primary lining, reducing the accelerator to leave the surface workable for a period of time so that a finishing team can follow the spray team, again trowelling off the surface

A plaster flat surface is impractical in tunnelling and is not required. What is necessary is to close up the surface and remove the protrusions so the membrane is not disrupted.

Substrate preparation in this way means less material is used when the waterproofing membrane is applied, and fast application is possible. A watertight structure is also then possible, as long as the membrane can be tested in situ to prove all areas have been covered.

3.2. Quality Control

It is the case that sheet membranes are manufactured under factory conditions and could therefore be considered to be continuous and defect free. However, handling and installation on site may cause damage and the seams are a concern as stated earlier. With sprayed membranes, the material is delivered to site as a liquid for some systems or as a dry powder for others, and spray applied. The same degree of quality assurance is necessary and this requires the following:

- Appropriate application methods
- Continuous monitoring during application
- Post installation testing to prove integrity

3.2.1. Appropriate Application Methods

Control is required in the application of these materials. It is relatively simple and operatives not familiar with these materials can be trained to install the products, following detailed application guidelines. However, if we are designing for dry, then control in the application is important – both to achieve a consistent thickness and to achieve complete coverage. There have been examples of remote controlled spray equipment such as spray concrete robots being used for this, although it needs to be questioned whether such equipment has the degree of accuracy to be able to install a 3mm consistently thick layer. Robots seem attractive as a way of reducing access requirements in a tunnel. However, even if a system is remotely applied, all sprayed systems then require examination or testing to ensure they application is continuous (with no defects in it) and so it is still necessary to get operatives close to the substrate. Therefore, regardless of whether robotic spraying equipment is used, suitable safe access will be required to get operatives within 1m of the sprayed surface throughout the structure. Proprietary access may be the answer for a tunnel of constant dimensions, or a system scaffold built access platform may be suitable.

Figure 1: access platform enabling application to 360^o of the tunnel

Figure 2: system scaffold providing access from multiple platforms

3.2.2. Continuous Monitoring During Application

As a sprayed membrane has a thickness build up in a number of passes it is important that the final thickness of the membrane is monitored in real time. This is achieved by an operative "wet film dipping" the thickness as spraying proceeds - measuring the depth of wet material and directing the sprayer if more material is required. This is important as materials can be opaque when relatively thin, but as waterproofing capability is related to thickness, it is necessary for the correct thickness to be achieved in a controlled manner. Thickness can be difficult to control if building up a single thick layer in multiple passes. Stirling Lloyd's long experience with sprayed membranes confirms the use of a two coat system that promotes thickness control and reduces the chances of defects.

Figure 3: wet film thickness testing during spraying

Figure 4: spraying membrane to invert

3.2.3. Post Installation Integrity Testing

This is perhaps the most important aspect of sprayed waterproofing membranes and one that can provide the engineer with complete confidence that a complete effective waterproofing membrane has been installed. Due to the increasing use of sprayed membranes in SCL tunnelling, the British Tunnelling Society (BTS) have incorporated it into their latest specification for tunnel linings (2). This advocates the use of non destructive in situ testing of the surface. In practice this means a qualitative testing system called "holiday testing" or commonly referred to as "spark testing". It is a method of passing an electrically charged brush over the surface of an insulating waterproofing membrane. If there is a defect, of any size, this system will be able to detect it. A systematic method is then required to divide the surface up into panels, testing them and marking any defects, or marking as defect free. Any defects can then be repaired and the resultant installation is completely continuous and therefore watertight.

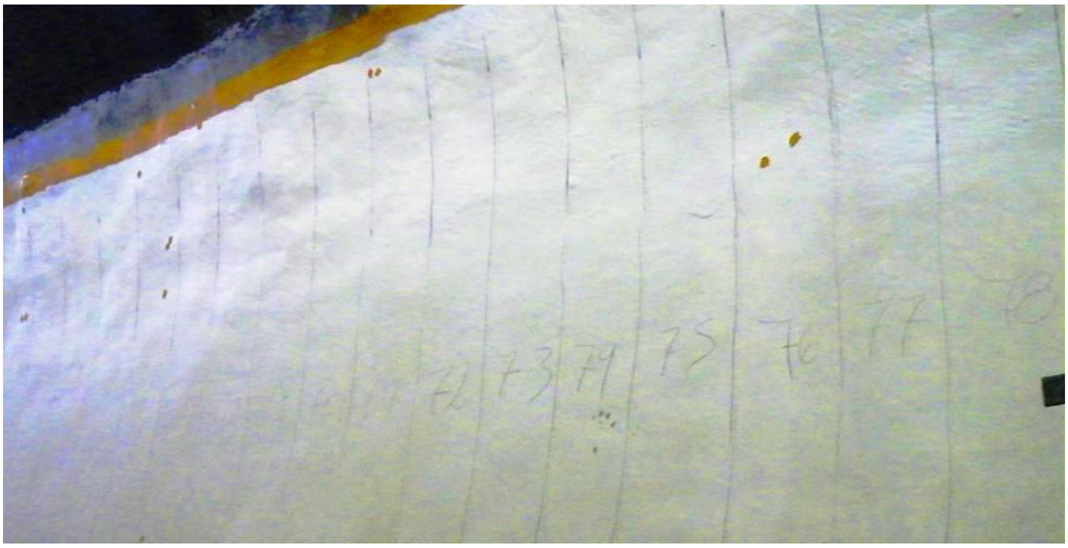

Figure 5: membrane surface divided into numbered test panels

3.3. Active Water Ingress

It is common in tunnelling for water ingress through the primary lining. This will vary from site to site depending on the geology, the level of water in the ground and any local measures used during construction such as dewatering. Sprayed waterproofing membranes cannot be sprayed on running water. The reason is that the membrane needs to achieve a good bond to the primary concrete and if a film of water exists between the membrane and the concrete, such a bond will not be formed. Damp concrete substrates are not a problem for some systems such as Integritank HF which has been designed to be applied to damp concrete but flowing water needs to be managed. This would usually be done by normal methods such as local dewatering, grouting or resin injection depending on the extent of water ingress. Sprayed waterproofing membranes are not intended to stop active water ingress during construction and should not be used for this purpose.

4. DETAILING

With many operations, it can be the fine detailing that proves more of a difficulty than large scale applications. This is the case with waterproofing, and because water under pressure will always find a way through if a water path exists, then attention needs to be paid to detailing. This is best done in advance of the installation, as most detailing requirements can be anticipated in advance. One example is penetrations through the membrane. In general terms, a preventative approach should be taken. Is it really necessary for a penetration to pass through the waterproofing membrane? For example a fixing anchored into the secondary lining, can it be designed such that it stops short of the membrane? If not, this item can be detailed to be waterproof, but application to a detail agreed in advance will likely prove more successful than leaving it to the operative on site.

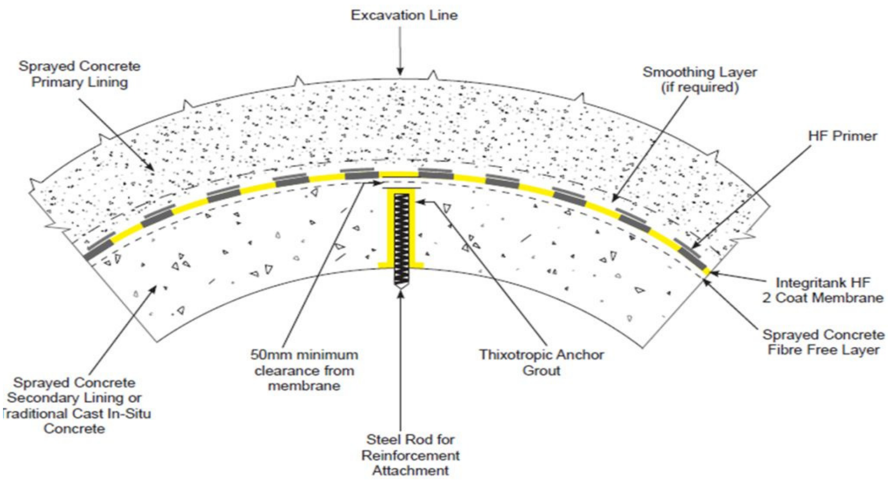

Figure 6: Penetrations should avoid going through the membrane where possible

5. HEALTH & SAFETY

There are many sprayed waterproofing system around the world that have been developed for various uses. However, it must be considered if the base technology of the membrane is suitable for use in the confined space conditions underground. Some materials have been offered for waterproofing underground which could have significant health and safety implications because they could provide an explosion risk or create a toxicity hazard. Sprayed waterproofing membranes used underground should have been designed for that specific environment, to avoid any such risks.

6. FURTHER DESIGN POTENTIAL

Where permanent high quality sprayed concrete has been used as the primary lining of an SCL tunnel and a sprayed waterproofing membrane like Integritank HF has been used to waterproof the structure, using sprayed concrete as the secondary lining, fully bonded to the primary lining through the waterproofing membrane (bonded both sides), there is the potential to consider the primary and secondary linings as acting together. Normally, any contribution that the primary lining might give to the strength of the lining overall is ignored because of the discontinuity between the 2 linings provided by a non bonded (both sides) sheet membrane, often with geotextile layers. However, if everything is in intimate contact and bonded together, the opportunity exists for designers to consider a contribution from the high quality concrete of the primary lining (3). This will of course depend on the structure and the local conditions, but there is the potential to decrease the thickness of the total lining thickness overall. This will have the effect of reducing the amount of material dug from the tunnel, reducing disposal costs, as well as reducing the amount of new concrete required overall. In addition, construction speed should increase. Therefore, using a spray applied membrane could have much wider potential than just the creating watertight underground spaces.

7. CASE STUDY: BUENOS AIRES METRO LINE B

Line B is part of an extensive network of metro lines that serve the Argentinean capital of Buenos Aires. There has been extension of a number of lines in recent years and the latest extension is to complete Line B. Tunnelling in Buenos Aires is almost exclusively NATM due to the favourable ground conditions and the progressive nature of the way the metro has been constructed in discreet packages. The structure to complete Line B was to be 2 large caverns that form the parking garage for rolling stock and workshops. The specification was for completely dry caverns. The garage cavern is a very large structure – 18m wide and 11m high. Support during excavation is provided by lattice girders and a primary lining of sprayed concrete. The secondary lining is a cast in situ reinforced concrete invert and above axis is a sprayed concrete secondary lining, varying between a minimum of 400mm and a maximum of 600mm thick. The concrete mix is a locally sourced 20mm maximum aggregate size sprayed concrete and the secondary lining is unreinforced.

Figure 7: Buenos Aires Line B garage cavern

Integritank HF from Stirling Lloyd was selected by main contractor Benito Roggio for this project because a watertight specification was required by the client Sbase. The construction period was quite short at around 18 months for this very large cavern, and so the sprayed concrete / sprayed membrane / sprayed concrete specification assisted a rapid build sequence. The nature of the 20mm sprayed concrete was coarse as an as shot finish, so the as shot surface had a concrete render applied to it and trowel finished. This provided an undulating surface, partly because of lattice girders in the primary lining, but a closed finish for providing a good substrate for the membrane.

For the installation of the membrane, a local contractor was selected by Benito Roggio and trained on site by Stirling Lloyd. The application in total is around 20,000 sq m but the fast track programme required that the waterproofing was installed in numerous areas. Therefore simultaneous application in different areas was undertaken, with a strict quality control regime on the use of lap joints to link different sections together. With Integritank HF, the material bonds to itself at the molecular level so lap joints become monolithic creating an effectively seamless membrane. This means waterproofing does not need to be a single continuous operation that prevents all other activities in that area. If required, sprayed waterproofing can be programmed in around other tasks without detriment to the final result. For Line B, the whole membrane surface was subjected to electrical integrity testing, proving that the completed membrane was free from any defects.

Figure 8: Integritank HF application along axis on both sides

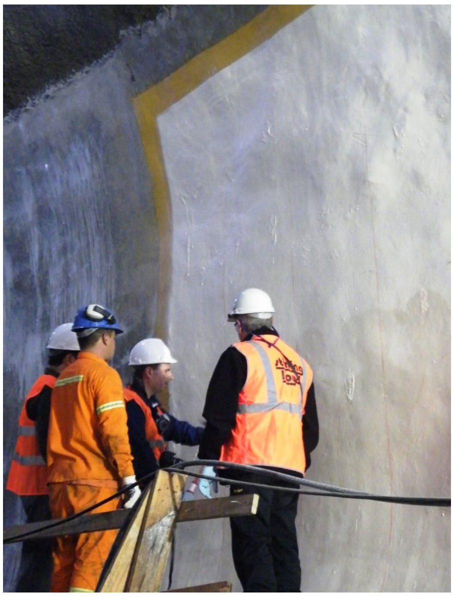

Figure 9: tidy edge terminations facilitate clean, effective laps

Figure 10: High voltage holiday testing to confirm integrity of membrane

After the waterproofing was completed, the secondary sprayed concrete lining was applied directly to the cured membrane surface. The secondary concrete creates a high bond strength to the cured membrane surface and the full thickness of 400mm in the crown was built up in successive layers.

8. CONCLUSIONS

Whilst the use of sprayed membranes in SCL tunnelling may be relatively new, the use of sprayed membranes in civil engineer to provide high levels of water tightness is well established. For tunnelling, the key is to understand the specific conditions presented by underground construction and use materials specifically designed for this environment. Most important is understanding the limitations of any material and ensuring that such limitations are made clear at the start and allowed for in the build sequence. Many claims have been made of sprayed waterproofing materials, but it is clarity on what they really can and cannot do, that will enable tunnel engineers to deliver tunnels with effective waterproofing, that should enable a greater level of water tightness than has so far been possible. As the use of underground space becomes ever more important, and where the emphasis is on long design life and performance, sprayed waterproofing provides an opportunity to provide greater levels of water tightness.

When used in conjunction with sprayed concrete secondary linings, and with the possibility of making use of composite action between the primary and secondary linings perhaps leading to thinner linings overall, sprayed membranes can enable the reduced overall cost for the membrane and secondary lining and faster build speeds, in addition to new levels of water tightness.

9. REFERENCES

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** LaserShell is a Morgan Sindall / Alpine Bemo Tunnelling development*