Waterproofing Sprayed Concrete Linings - Existing Methods and Potential Developments

Sivanathan Sivakanthan[1], Pedro Ferreira[2], Peter Wright[1] and Don Wimpenny[4]
[1]*Tunnelling and Ground Engineering, Jacobs, London, U. K*
[2]*Department of Civil Engineering, University College London, London, U.K*
[4]*Asset Management, Jacobs, London, U.K*
E-mail: sivanathan.sivakanthan@jacobs.com

ABSTRACT: Sprayed concrete tunnel linings are a popular solution to the increasing need for fast and efficient transport systems in urban environment worldwide. Achieving an acceptable level of watertightness in sprayed concrete linings with a view to increasing the speed of construction, reducing costs and improving the carbon footprint remains a significant challenge for the construction industry. Sheet and sprayed membranes and, to a lesser extent, integral waterproofing admixtures are currently being used for achieving the required level of watertightness. Each of these technologies have advantages and disadvantages, which determine their suitability and ease of use in a particular project. This paper examines the existing technologies and outlines emerging technologies in the concrete admixtures that have the potential to control the water penetration in a sprayed concrete tunnel lining. It describes the laboratory work carried out using integral waterproofing admixtures as part of research in the UK towards the development of a one-pass watertight sprayed concrete tunnel lining, where different admixtures were tested using conventional tests normally performed in the industry and a modification of a standard test to reveal the benefits of the use of technologies such as crystalline and Polymer Latex additives to reduce the permeability of the joints over time.

KEYWORDS: Sprayed Concrete Tunneling, Waterproofing, Integral permeability reducing admixtures, Sustainability

1. INTRODUCTION

Sprayed Concrete Tunnels are a popular solution to the increasing need for fast and efficient transport systems in urban environments worldwide. For shorter tunnels (less than 1km long) with varying geometry and junctions, the use of a sprayed concrete lining (SCL) is an efficient and cost-effective construction technique.

The design life of underground structures is commonly expected, by the asset owner, to be more than 100 years. The expected structural and functional requirements of the tunnel lining during the entire design life are that the lining:
a) maintains its ability to carry loads; and
b) satisfies desired watertightness with minimal or no maintenance.

Over the last 30 years, the continuous development of sprayed concrete materials, spraying equipment and technology, testing and quality assurance have led to the primary tunnel lining being designed as a permanent rather than a temporary structure. This allows a reduction in the total lining thickness. For example, in the recent Bank Station upgrade project (UK), the thickness of the linings was reduced by up to 15%, by considering both primary and secondary as permanent lining but without allowing for any composite action between the linings (Smith, K.2019). Therefore, constructing the tunnel without a waterproof membrane while facilitating the composite action between the primary and secondary linings will lead to the linings becoming even thinner and with a corresponding reduction in excavated material. This will have a positive impact on the sustainability and utilisation of tunnels and other underground spaces.

The 2018 report by the Intergovernmental Panel on Climate Change (IPCC, 2018) makes it clear that immediate action is required to limit global warming. At the Paris climate conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. The UK government recently committed to zero carbon emissions by 2050. Portland cement is the source of about 8% of the world's carbon dioxide emissions (Rodgers, L.2018). Therefore, reducing cement usage on underground infrastructure projects is vital and can make an important contribution to addressing climate change.

The existing construction methods for SCL seem to be overly conservative and this is mainly due to the adopted waterproofing and associated construction techniques. Sprayed concrete mixes can be designed with a low permeability, similar to conventionally cast concrete. However, during construction, cracks are likely to develop within the lining, particularly at the joints between subsequent advances due to early thermal and shrinkage effects. These provide a path for water penetration.

1.1 Acceptable water ingress limits for SCL

The water leakage requirements for tunnels differ between countries and are covered in various tunnelling specifications (e.g. BTS (UK), DIN 4030, ITA 1991 etc). Specifications often include watertightness classes to reflect the intended use of the space. These typically place limits on the presence of water at the intrados and the flow of water though the lining. The ICE (UK) BTS specification specifies the water leakage criteria according to a class of tunnels and is shown in Table 1.

Table 1. Watertightness classes (after BTS,2010)

Class	Typical use	Description	Daily Limit*
1	Storage rooms	Absolutely dry No damp patches	0.01
2	Road tunnels with frost risk	Substantially dry Damp patches not discoloring blotting paper	0.05
3	Road and rail tunnels	Capillary dampness Damp patches but no droplets	0.1
4	Utility tunnels	Small amounts dripping water	0.2
5	Drainage/sewer tunnels	Dripping water	0.5

* leakage in litres per square metre of tunnel lining

Integral permeability-reducing admixtures have been used in concrete for more than a century. Their appropriate use in combination with improvements in SCL technology over the last three decades should, in principle, allow construction of watertight tunnel linings. The acceptability of this approach depends on the intended use of the underground space and the associated watertightness requirements.

Single shell linings (SSL) formed with multiple layers offer the possibility of cost and programme benefits and have occasionally been used below the ground water level. However, the watertightness is very reliant on the performance of the joints. Therefore, the focus of this study has been to identify appropriate permeability-reducing admixtures that have the potential to achieve the required level of watertightness in a sprayed concrete tunnel lining. Issues related to the existing construction methods and waterproofing techniques will also be discussed in this paper, along with an example from the Crossrail project, regarding the hydraulic conductivity, watertight tunnel lining and joints.

2. BACKGROUND

2.1 Construction Methods

The traditional construction method of SCL tunnels and shafts is known as double shell lining (DSL). DSL consists of a temporary sprayed concrete primary lining reinforced with mesh and lattice girders, along with the secondary lining constructed from conventional cast-in-place concrete with steel rebars. Depending on the watertightness requirements, either no waterproofing or a sheet membrane is used between the primary and secondary linings. Due to continuous improvements in construction techniques and concrete material technology, the traditional practice of treating the primary lining as temporary or sacrificial results in an overly conservative and wasteful design (Thomas, A & Dimmock, R 2017).

The emerging SCL design approach is to consider the primary lining as part of the permanent works. This allows the lining to be designed as:

a) A DSL with reduced secondary lining thickness;
b) A Composite Shell lining (CSL); or
c) A Single Shell Lining (SSL);

The benefits of option a) are limited by the cost, complexity and mainly the time associated with installing a waterproof membrane. This membrane also prevents strain compatibility between the primary and secondary linings.

CSL consists of steel fibre reinforced permanent primary lining. The spray waterproof membrane is applied together with the regulating layer in such a way that it is sandwiched between the primary and secondary linings. The secondary lining is constructed as either conventionally cast-in-place or sprayed concrete. The composite action between the primary and secondary linings requires strain compatibility and this relies on the structural bond and the transfer of shear between the linings and across the sprayed waterproofing. Depending on the bond and the shear interface between the linings, the composite action can be treated as full slip, partially composite or full bond. Using the above assumptions, primary linings can be designed to bear the full temporary load and a proportion of the permanent load. The secondary lining is then designed considering the remaining permanent load through the composite action.

The total lining thickness CSL depends on the degree of composite action. The presence of a waterproof membrane allows some shear strain between the linings, but not interlocking. Diez et al (2019) noted that even though various authors (Holter et al 2011, Pickett et al 2013, Su 2016, Pillai et al 2017) have claimed that the adoption of the composite lining concept would lead to a significant reduction in the secondary lining thickness this has, so far, not been widely implemented in the design of SCL tunnels in soft ground. The authors mentioned that this is mainly due to the moisture sensitivity of the membrane and the reduction in its properties (tensile strength, initial Youngs modulus, tensile bond strength and effective Youngs modulus) with time.

Based on the laboratory trials carried out using EVA (ethylene vinyl acetate) powder-based and reactive resin-based spray membrane products for the Crossrail project, Diez et al (2019) indicated that the long-term effective stiffness of the spray-applied membrane would be substantially lower than short-term values. In addition, the long-term effective stiffness of the spray-applied membrane is expected to be less than the long term stiffness of the sprayed concrete and this raises questions about the degree to which composite action can be assumed. The impact of composite action behavior was investigated by Su (2016) using a 2D numerical modelling. Based on his study, Su (2016) concluded that the load sharing is a complicated issue and depends on many factors. He mentioned that the parameters and assumptions regarding the long-term behavior of the spray applied waterproofing systems are the key uncertainties.

Golser & Kienberger (1997) noted that measurements for real tunnels have shown that the secondary linings are often not carrying the loads that would be expected, based on the assumptions that that primary linings would disintegrate. Thomas & Dimmock (2017) demonstrated that the secondary lining serves no structural purpose and proposed that a minimal thickness would be adequate to use as a fire protection layer for the spray-applied membrane. All these findings emphasise that the primary lining needs to be designed to carry the full load for the entire design life of the structure.

2.2 Waterproofing techniques

SCL tunnels are typically subjected to a high hydrostatic head during construction and in the longer term. The tunnels are generally waterproofed by use of sheet, spray-applied membrane and, to a much lesser extent, the use of watertight concrete (crystal growth) systems (McGrath, 1998). However, to meet the most onerous watertightness classes, construction of an additional internal lining with a drained cavity may be required. This is primarily due to the potential leakage at the joints.

The traditional method of waterproofing is to use a sheet waterproof membrane, with a cast in-situ concrete lining inside it. The membrane is typically PVC (polyvinyl chloride), unbonded to the primary lining. It has a geotextile fleece which will allow drainage of water behind the membrane, where it will be intercepted by a drain. In this way, water pressures acting on the secondary lining are minimised, although the pre-existing ground water regime may be affected. To minimise pumping requirements, grouting may be used behind the primary lining during the construction of primary lining.

In contrast to sheet membrane, spray-applied membrane systems are constructed without any drainage measures. The membranes are relatively thin and typically the total thickness is in the range of 3-4 mm. Depending on the design requirements and product chosen, sprayed membranes may bond to both primary and secondary linings (double-bonding) or only to one lining (single-bonding). Therefore, unlike sheet membranes there should be no possibility for water to travel between the concrete and membrane, should the latter be breached. In cases where water passes through any crack or joints in the primary lining it will apply pressure locally on the sprayed membrane. Otherwise, water would need to penetrate through the full thickness of the primary lining where the hydraulic conductivity and porosity of the concrete permits. This is discussed further in Section 3.

2.3 Advantages and Disadvantages of the existing techniques

Sheet membranes are produced in a controlled environment with constant thicknesses, whereas the thickness of sprayed membranes depends on site workmanship and testing. Proper comparison of waterproofing options should consider not just their performance in a short time, but also the full economic cost over the design life of the tunnel.

One of the drawbacks in using a sheet membrane system is its potential for damage, causing leaks that can be difficult to trace back to the source. The high labour cost and sometimes complex nature of the installation at junctions, have also been a drawback to the use of sheet membranes. However, different coloured layers are now being introduced into membranes to help identify damage during installation. The success of the sheet membrane waterproofing installations also depends on secure overlapping joints between sheets, connected using welding or adhesives.

Spray applied waterproofing has potential maintenance and repair benefits in the long term by preventing the movement of water. If there is a leakage on the extrados of the secondary lining, as the water is not able to move laterally, the source can be easily located and treated. In addition, sprayed membranes can be applied without the risk of folding and stretching and, in isolated areas, without the need to consider continuity and sealing joints at the perimeter.

Spray applied waterproofing methods can be installed onto complex geometries at a lower labour cost compared with the sheet membrane method. However, the application is not that straightforward and requires significant care and expertise. Many manufacturers recommend that the membrane should be applied on top of a relatively smooth regulating layer of sprayed concrete, which has no steel fibres and a finer aggregate grading. Thomas, A & Dimmock, R (2017) noted that the performance of spray applied membrane is heavily dependent on the preparation of the substrate.

It should be noted that extensive research work carried out by Holter (2015) on the possible use of spray-applied membrane as a permanent solution for tunnels in the hard rock environment (which is exposed to groundwater under low to moderate hydrostatic pressures) revealed that:

- Delamination of the membrane under pore water pressure, softening and reduction in tensile bond strength is possible due to exposure to saturated conditions. Therefore, membranes need to be installed in the lining in such a way that there is protection from degrading mechanisms.
- EVA based spray membranes, together with the sprayed concrete lining can be considered as a waterproof system but it is not vapour impermeable. This allows migration of water through the membrane in the form of capillary and vapour diffusion mechanisms.
- Cracks in the concrete intersecting the membrane may expose it to high water pressure resulting in debonding failure at the interface or adhesive and shear failure of the membrane, depending on the properties of the membrane.
- The long-term durability of the membrane is dependent on the moisture condition, which is potentially increased at cracks and joints in the lining and in areas of higher porosity due to the spraying process, e.g. sand pockets in the sprayed lining.

All in all, the traditional DSL is potentially over-conservative but the principal limitation in the design of CSL is the degree of composite action. This leads to the secondary lining to be designed as an uneconomically thick lining. A certain thickness of secondary lining is required to avoid damage to the waterproofing membrane, to allow the fixing of any tunnel utilities and to be used as fire protection layer.

As mentioned in section 2.3 the spray membranes need to be installed after a certain thickness of primary lining concrete to avoid delamination and degrading effects from exposure to any saturated conditions. Given the location of the spray applied membrane, delamination and degrading mechanisms are highly dependent on the quality of the primary lining. With developments in sprayed concrete technology the quality and the watertightness of the primary lining have significantly improved over the last 30 years. This prompts the questions:

- What is the hydraulic conductivity of the primary lining, both generally and at construction joints?
- Will water ever reach the membrane during the design life of the structure?
- Would water ever reach the intrados of the lining, even if no membrane is installed?

3. OBSERVATIONS

3.1 Literature Review

State-of-the-art sprayed concrete technology has led to the use of primary SCL with enough load-bearing capacity for the entire design life of the structure. On the Crossrail project and more recently in the Bank station upgrade project, the primary lining of the sprayed concrete structures was considered as permanent lining. Therefore, controlling the water ingress through the primary lining, at least to a degree that satisfies the tunnels functional requirements, would reduce the need for waterproofing techniques. This would also reduce the overall lining thickness.

3.1.1 Watertight tunnel linings

The criteria for the acceptance of sprayed concrete as a waterproofing element for tunnels varies from country to country. In Norway, for a sprayed concrete mix to be considered watertight, it should have a permeability coefficient in the order of 10^{-12}m/s (Astad and Heimli, 1988). The watertightness criteria depend on the usage of the tunnel and, in many places, it is defined as an allowable leakage rate rather than hydraulic conductivity (Table 1). However, it is necessary to know the hydraulic conductivity of both the lining and joints to design for the allowable leakage rate.

The Crossrail project in the UK can be used to assess the hydraulic conductivity in order to achieve a watertight lining, including at joints. Three water leakage limits were defined for the Crossrail tunnels:

Trainway and general access tunnels

- Above axis: Free from seepage & damp patches
- Below axis: Damp patches, minor weeping of joints less than 0.24 litres/day/m^2

Other tunnels not accessible to public

- Damp patches and minor weeping of joints – 1.0 litre/day/m^2 with an average below 0.1 litres/day/m^2.

Crossrail's deepest tunnel axis is approximately 45m below ground level. Considering a steady-state water flow condition, a 300mm thick primary lining subjected to a hypothetically 50m head of water would need to have a hydraulic conductivity not exceeding 7 x 10^{-13} m/s to meet the BTS Class 1 watertightness criteria (Table 1), which is equivalent to being free from seepage and damp patches and would also meet the most onerous requirement among the three leakage limits for Crossrail. However, this calculation ignores the positive effect of evaporation and the negative impact of joints. The latter is a critical consideration for designing the tunnels without any waterproof membranes.

Since the hydraulic conductivity of 7×10^{-13} implies a steady water leakage rate of 0.01 litres/day/m^2 through the primary lining, it would be beneficial to know how long it would take for water to penetrate the full thickness of the lining and for the steady state flow to become established. This would help to decide the waterproofing requirements.

Valenta (1970) proposed the following equation for predicting uniaxial penetration of water into the concrete:

$$x = \sqrt{\frac{2kht}{\nu}} \qquad (1)$$

Where x is the depth of penetration at time t, k is the hydraulic conductivity, h is the pressure head and υ is the porosity of the concrete. Based on 50m head of water and Crossrail mix design porosity value of 0.2, the variation of uniaxial penetration of water into the lining with time are presented in Figure 1 for varying permeability values. If the Crossrail lining hydraulic conductivity value is 7 x 10^{-13} m/s (equivalent to a BS EN 12390-8 test value approximately half the specified limit of 25 mm) then water is predicted to fully penetrate the 300mm thick lining in approximately 8 years. Whereas, if the hydraulic conductivity of the linings is 10^{-13} m/s, it would take more than 60 years for the water to penetrate the lining, whilst at 10^{-14} m/s the water will not reach the intrados of the 300mm thick primary lining during the 120-year design life.

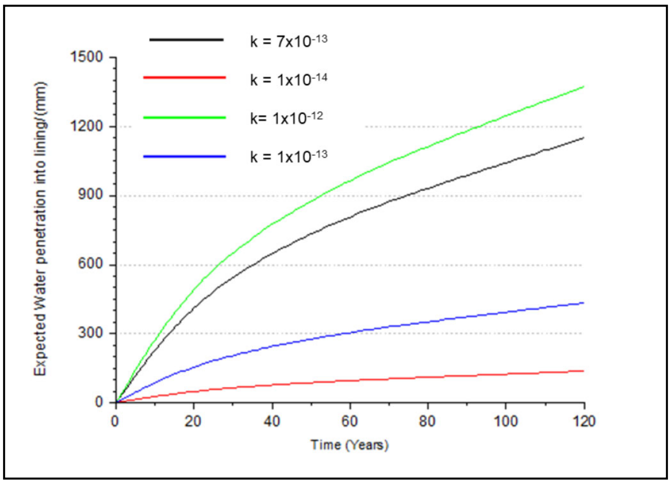

Figure 1 Prediction of long-term water penetration using Valenta's equation

According to the literature, the hydraulic conductivity of sprayed concrete lies in the range of 10^{-12} to 10^{-14} m/s (Thomas 2008, Gomes 2005). However, with the use of micro silica, avoidance of lattice girders and continuous improvement in the mix design along with the material and construction methodology, the hydraulic conductivity of a sprayed concrete lining is expected to be less than 10^{-14} m/s. It should be noted that, more recently, Holter (2015) reported that the values of the hydraulic conductivity would be less than 5x 10^{-14} m/s.

It should be noted that the above calculations for the time required for the water to fully penetrate the primary lining ignore cracks and joints. The time would be much shorter at crack and joint locations.

Cracking of the lining will arise due to flexural, early-age thermal stress, autogenous shrinkage and, to a lesser extent, early ground loading. Most cracking will occur in discrete lengths and not run through the full thickness of the lining. It should be noted that cracks are minimised, and crack widths are controlled by the presence of steel or synthetic fibres. These cracks are expected to heal by self-healing. However, in contrast to the lining, joints can be a substantial discontinuity that runs through the full thickness of a lining, with implications for hydraulic conductivity and achieving watertight tunnels.

Water paths in the joints can be intercepted by staggered joints in the primary lining. Therefore, a single shell lining, which is constructed in multiple layers with staggered joints, can be considered watertight once the joint's hydraulic conductivity is less than 10^{-14} m/s.

3.2 Single Shell Tunnel Linings

With the development of material and construction technology, constructing a relatively thin and watertight Single Shell Lining (SSL) in multiple layers (without the waterproof membrane) would be economical and more sustainable.

The improvement in admixtures, improved fibre technology and application methods, such as staggered joints that could control the water ingress, have created opportunities to build a watertight, durable and economic lining system in the form of a single sprayed concrete lining permanent shell.

The SSL concrete needs to be pumped and sprayed easily, have a fast set and strength gain with low potential to crack. It is particularly important to have joints with low permeability and durable for the entire design life of the structure. For watertightness, the lining should be constructed in a few layers. In the design each layer is expected to act monolithically with the previous layer, therefore the interlayer bond should be tested to ensure adequate adhesion and shear resistance.

4. DEVELOPMENTS

4.1 Identification of Materials

Admixtures for waterproofing concrete have been used for over 100 years and a large number of these technologies have the potential for improving the watertightness and sustainability of sprayed concrete tunnel linings. However, these have rarely been used in sprayed concrete tunnel linings. After a thorough review, these technologies were reduced to a more manageable smaller number to be tested in this research project.

It is worth mentioning that fibre-reinforced geopolymer concrete has been used to produce precast tunnel segments with a 70% reduction in embodied CO_2 and with decreased shrinkage and permeability (Wimpenny et al, 2011). Sprayed concrete using alkali-activated cements have been developed for repair applications. However, the conflict between fast setting, strength gain and the desire to avoid alkali activators is challenging. In addition, difficulties in providing an adequate pot life and achieving a suitable mixing in the nozzle are some of the difficulties that need to be overcome. Given the concerns over the ability to develop a suitable geopolymer concrete for sprayed concrete tunnel linings, this option was discarded.

Permeability Reducing Admixtures (PRA) were identified for testing based on compatibility with sprayed concrete and ability to:

- Repel the water from the lining boundary
- self-heal cracks and joints
- block capillary pores
- reduce shrinkage and reduce permeability.

4.2 Laboratory Studies

Four different PRAs and two combinations of admixtures were selected and tested by incorporating them in the sprayed concrete mix. These are:

- Hydrophobic (H)
- Pore Blocking (PB)
- Hydrophobic pore blocking (H+PB)
- Crystalline (C)
- Polymer latex (PL)
- Crystalline & polymer latex (C+PL).

The sprayed concrete mix and the details of the admixtures are given in Tables 2 and 3. The base mix design is a pre-blended dry silo mix approved for use in a tunneling scheme in London.

Table 2: Summary of base mix design

Component	Approx. quantity per cubic metre
Portland cement	440 kg
Aggregate 6mm	335
Sand (4mm)	1341
Silica fume (6%)	28 kg
Aggregate	1700 kg
Water	176 kg*
Steel fibres	35kg
Superplasticiser	2.2 litres
Retarder	0.11 litres
Accelerator	3%

Viscosity modifying admixture	0.13 litres

* water/cement ratio of 0.40

Table 3: Permeability reducing admixtures

Admixture type	Approx. quantity per cubic metre
Hydrophobic (H)	1.5% by mass of cement
Pore Blocking (PB)	8 litres
Hydrophobic pore blocking (H+PB)	30 litres
Crystalline (C)	1.8% by mass of cement
Polymer latex (PL) Styrene butadiene rubber (SBR)	132 litres
Crystalline & polymer latex (C+PL)	1.8% by mass of cement plus 132 liters respectively

The amount of water already within the admixtures was considered when calculating the amount of water required to obtain the final water/cement (w/c) ratio of 0.4 for all the concrete mixes. In the laboratory trials none of the mixes had steel fibres and all samples were conventionally cast rather than sprayed. An alkali-free accelerator was added before the casting at a dosage of 3% by mass of cement for all tests (accelerator was not added to the testing samples).

The acceptance criteria applied to the sprayed concrete is based on the specification for the Crossrail project, as summarised in Table 4 (Crossrail, 2012).

Water penetration, water absorption, compressive strength and drying shrinkage tests were carried out on all PRA modified mixes. The results were compared against the control mix results and the acceptance criteria for SCL tunnels (Table 4)

Table 4: Summary of acceptance criteria

Parameter	Method	Limit
Consistence flow table	BS EN 12350-5	500-600mm
Concrete temperature		15-35°C
Early strength gain stud penetration	BS EN 14488-2	Modified J2 curve BS EN 14487-1
Drying shrinkage	ASTM C341	0.03%
Water penetration (mm)	BS EN 12390-8	35 (individual) 25 (average)
Long term compressive strength	BS EN 12390-3	28/30*

* characteristic strength cylinder/cube

High early strength development and no strength loss at later ages are vital for permanent sprayed concrete lined tunnels. Initial, early and long-term strength measurements of the samples were carried out using a digital penetrometer, Hilti DX 450-SCT powder-actuated tool (stud driving test) and cube compression test machine respectively.

Water penetration tests were carried out on all the samples in accordance with BS EN 12390-8. In addition, water absorption tests were carried out according to BS 1881-122:2011 to understand the effect of PRAs in controlling or preventing the capillary transport of water through the sprayed concrete.

Apart from early-age thermal contraction and autogenous shrinkage, drying shrinkage occurs in tunnel linings and further increases the potential for cracking in the lining and joints in the long term. Therefore, drying shrinkage tests were carried out on all mixes according to ASTM C341-96.

A rheometer was used to measure the yield stress and plastic viscosity of the concrete mixes and the results were compared against the control mix. This test was required to understand the pumpable and sprayable consistencies, together with the retention time of the mixes. An isothermal calorimeter was used to measure the heat released as the hydration reactions take place. These tests were important because of the potential impact of the addition of PRAs on the rheology and hydration of the mixes. To test the effectiveness of the PRAs, cubes were cast in two halves with one day interval to form a construction joint (Figure 2). Once the cube was cured, the joint was exposed to water under 5-bar pressure following the procedure for water penetration specified in BS EN 12390-8. After the test the cube was split to reveal the depth of water penetration. Three samples were prepared and, tested at the age of 28days, with the average value being reported for each test.

Figure 2: Jointed sample before and after the water penetration test

Given that the standard equipment (Figure 3) only offers the option to apply a vertical force, it was noticed that the 5-bar pressure applied at the bottom of the sample tended to split the sample through the joint; a G-clamp was then used to maintain the sample intact (seen on the first concrete block on Figure 3).

Figure 3 : Extended water penetration test setup

This is an important observation as it highlights the poor adhesion that exists in the created joint. Preliminary laboratory test results identified the C and C+PL modified mixes, along with the Control mix, to be tested in the water penetration equipment for an extended time period. The original water penetration equipment was modified by the addition of a cylindrical air water interface made of plexiglass. This allowed the volume of water passing through the sample to be measured continuously over long periods of time. Figure 3 shows the air-water interfaces with a simple sheet used to mark the water level, together with the date and time; in some samples, this was measured for a period longer than a month.

4.3 Laboratory test results

The rheometer results are summarised in Figure 4. The control mixture (or target) has a yield stress of 250Pa and a plastic viscosity of 25Pa.s. The yield stress is related to the force required to break the structure and initiate the flow, whilst the plastic viscosity describes the resistance of the mix to movement. Given that this is a widely used mixture, it was assumed that it has the desired properties of a sprayed concrete mix, i.e. optimum pumpability and workability for spraying; therefore, the values obtained were assumed to be target values for other possible mixtures. Additional mixes were produced at different w/c ratios and, by looking at the control mix, it can be seen that changing the w/c from 0.4 to 0.45 caused a large reduction in Yield stress and a small reduction in viscosity, as expected (Tattersall et al, 1983). The mixes containing polymer latex are associated with the lowest yield stress and this is believed to be due to the lubricating effect of their spherical particles. Reducing the w/c ratio to 0.37 for the C+PL mix increased the yield stress closer to the target value, but also resulted in a higher viscosity. It was considered that this could be advantageous as this would improve the sprayability of the concrete mix.

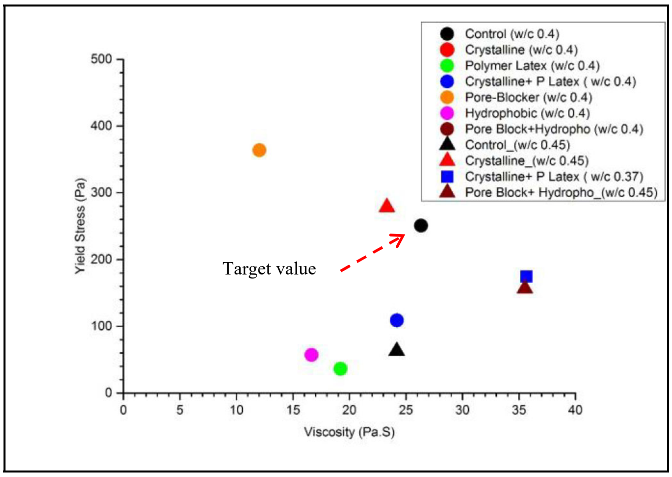

Figure 4: Rheology of sprayed concrete mix modified with PRAs

The compressive strength development of the mixes is shown in Figure 5, where the very early age strength (< 1 hour) of all the mixes lies below the modified J2 curve due to the use of low accelerator dosage (3%) for the preparation of the samples in the laboratory. The mixes with latex had the lowest early strength development due to its retarding effect. After 4 hours of age, all mixes, apart from the C+PL have a strength higher than the modified J2 curve. The lower initial strengths are expected to be mitigated as the common practice in the industry is to use a dosage of 6-8% accelerator; such percentages could not be used in the laboratory environment. Strength measurements were only made up to 28 days in this laboratory testing and all of the samples exceeded the requirement for 28 days strength. All the admixture combinations showed either stable or increasing trends of long-term strength development and this is beneficial for sprayed concrete application.

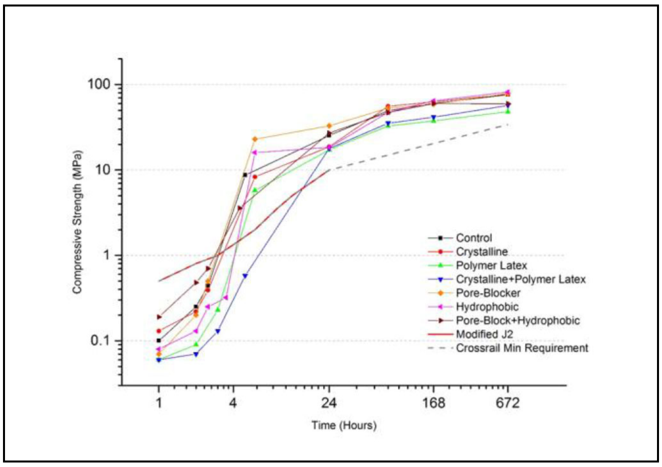

Figure 5: Strength development of the mixes

The effect of combinations of cement admixtures on the heat evolution is shown in Figure 6. The figure shows the heat generated by the hydration reactions, normalized by the sample weight, for the base mix (control mix without accelerator), the control mix and five other mixes modified with PRAs and its combinations. The authors would like to remind the reader that, with the exception of the base mix, 3% accelerator was used on all the mixes. Therefore, the difference seen in energy release (heat flow) between the base mix and rest of the mixes is considered to be due to the addition of 3% alkali free accelerator.

The slow rate of hydration seen on the C+PL combination is due to the presence of latex, as the crystalline mix only shows a higher rate of hydration. The retarding effect of the polymer latex is apparent in the isothermal calorimetry data, with these mixes giving rise to the lowest and latest heat flow peak (Figure 6). By combining the strength results and the calorimetry data it is clear that higher initial heat flows are met with higher initial strengths. Again, the authors have confidence that the low early age heat release and associated strength gain can be mitigated by the addition of larger percentages of accelerator, moving the heat peaks shown in Figure 6 further to the left, consequently increasing the initial strength.

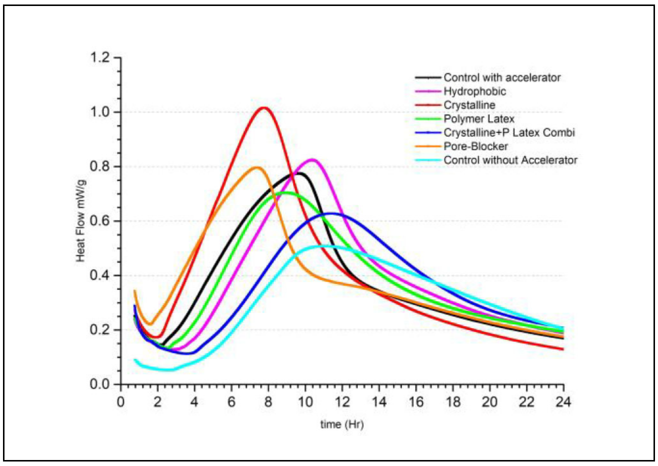

Figure 6 : Effect of cement- admixture combinations on heat evolution.

The drying shrinkage data is summarised in Table 5. The 28-day drying shrinkage values for all the mixes did not exceed the 0.03% limit noted in Table 5. The Crystalline modified admixture (C) shows lower shrinkage compared with the control mix and this might be due to the excess water used for the crystalline process leaving less to be lost. The lowest shrinkage occurred in the C+PL and H mixes. The effect of the polymer latex may be due to sealing of the capillary pores by a polymer film together with the use of water for the crystalline process.

The hydrophobic admixture lowers the surface tension of water and this is known to reduce shrinkage and related cracking (ACI, 2010).

Table 5: Drying Shrinkage

Mix	Shrinkage (%)	
	28-days	90-days
Control	0.0117	0.0120
H	0.0091	0.0110
PB	0.0119	0.0133
HPB	0.0130	0.0138
C	0.0105	0.0124
PL	0.0113	0.0107
C+PL	0.0085	0.0102

The average water penetration depth, for samples with no joint and with a joint are presented in Figure 7 and Figure 8 respectively. The mixes have a w/c ratio of 0.4 and include 3% accelerator.

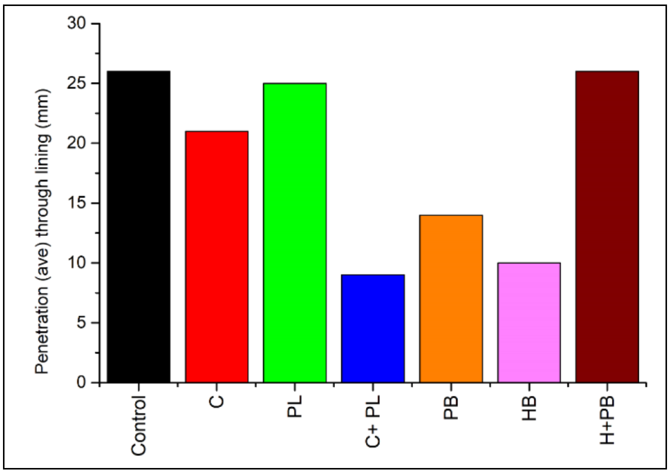

Figure 7: Water penetration (no joint)

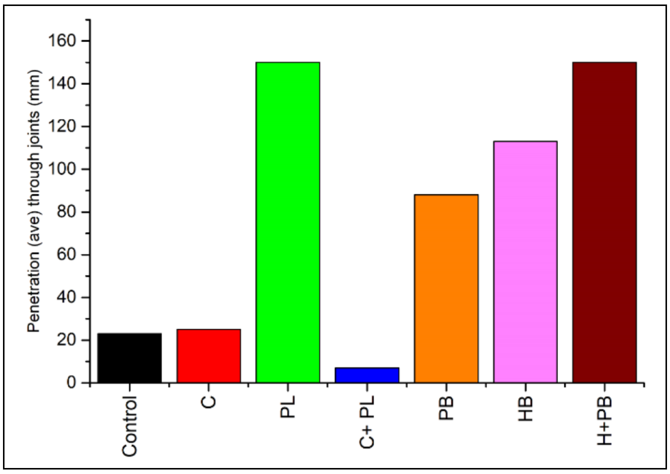

Figure 8: Water penetration (with joint)

By comparing the results of Figure 7 and 8 it is clear that the presence of a joint allows the water to travel further in the sample. The exception is the C+PL mix, which yields low penetration values of less than 10 mm for samples with and without joints; values that are much lower than the control mixture.

The results for the PL and H+PB mixes may not be correct due to problems related to mixing. The PL admixture was not mixed according to the specifications, justifying the poor values obtained. The H+PB had a lower than expected workability and the addition of accelerator made it worse.

As expected, Figure 7 shows that the hydrophobic admixture reduces the penetration of water by almost 60%, when compared to the control mix. This reflects the water repellent effect of the hydrophobic layer formed on the surfaces of the pores of the concrete. This H admixture is more effective in sprayed concrete mixes due to the smaller diameter of the capillary pores when compared with the normal concrete mix; caused by the addition of micro silica. However, as shown in Figure 8, the test carried out on the jointed samples that have the hydrophobic admix show the opposite results to those of the intact sample. The water penetration depth was almost 5 times greater than the control sample with a joint, confirming what has been mentioned in the literature. As the joint was created by pouring a second layer 1 day later, the hydrophobicity of the older concrete layer repels and reduces the movement of the water between layers, consequently reducing the hydration process across the joint. This effect causes poor adhesion between layers and the formation of pores that allow the water to penetrate easily through the joint. The joints are normally formed around 8-12 hours in sprayed concrete tunnel linings, when the majority of the hydration would have occurred as can be seen in Figure 6, particularly if higher amounts of accelerator are likely to be used. This implies that a hydrophobic admixture is not suitable to control the water penetration in tunnel linings, unless the joint is treated and the hydrophobicity is inhibited; adding another stage to the process of building the shell lining.

As shown in Figure 7, a reduction in water penetration of around 45%, when compared to that of the control sample was observed for the pore blocking admixture. However, almost 4 times greater water penetration to that of the control sample is seen for the sample with a joint. The test results suggest that as joint widths are greater than the capillary pore diameter, the pore-blocker particles could not seal them against water movement, due to the high external pressure. Therefore, it is likely that pore blocker will not be used to control the water penetration through joints in sprayed concrete tunnel linings.

The testing of joints in this manner does not simulate performance in a sprayed concrete lining, where early thermal contraction and shrinkage could be expected to open cracks in joints. However, it does indicate that the C+PL combination is the most effective admixture at reducing water penetration, particularly at joints, and to meet the penetration limit of 25mm. Based on the 9mm of water penetration depth this C+PL combination mix indicates an equivalent Valenta permeability coefficient of less than $7x10^{-17}$m/s at interfaces and away from the joint. As identified in the literature, the formation of a polymer film with its associated water retention properties, together with the addition of a crystalline admixture are the reasons for the lowest water penetration away from the joint's locations. Better bonding at the joint due to the latex admixture together with the presence of crystalline admixture are the reasons for the lowest water penetration through the joints.

Water absorption values at 7 and 28 days are shown in Table 6 . The water absorption at 30 minutes are less than 3% for all mixes, an indication of low values permeability (Concrete Society, 2008). The mixes with polymer latex have water absorption values 5 times lower than the other mixes and, unlike the others, the decrease in water absorption with age was negligible.

Table 6: Water absorption data

Mix	30-minute absorption (%)	
	7-days	28-days
Control	1.84	1.64
H	1.88	1.52
PB	1.90	1.53
HPB	-	0.72
C	1.62	1.55
PL	0.26	0.25
C+PL	0.24	0.30

Figure 9 shows the results of the extended water penetration tests carried out in the Control, C and C+PL modified admixtures.

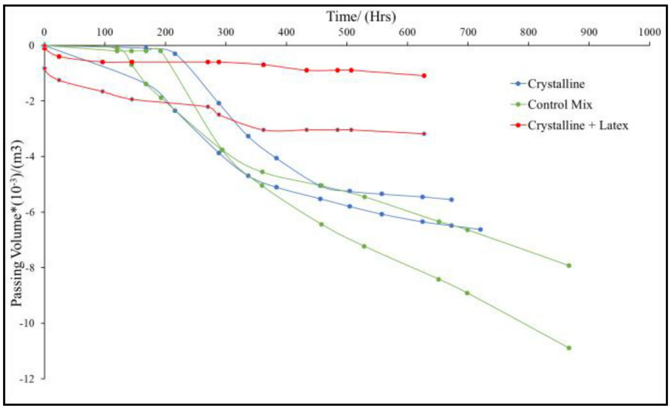

Figure 9: Water Penetration through joints for Control, C and C+PL modified mix samples

In the case of the control sample, it was observed that after a certain amount of time the rate of water flow falls over time, reaching a constant value that still allows the joint to continuously leak. The authors believe that the variation of flow rate prior to achieving a steady state is attributed to autogenous healing.

For the C mix, it was observed that the rate of flow through the sample initially is higher than the control mix, however it quickly reduces a much lower rate. A similar trend is seen in the C+PL mix, where the steady state rates are significant lower and seem to show a tendency to stop the leak through the joint. This is likely to be due to the formation of crystals during the hydration which then provide a resistance against the water flow.

The C+PL modified mix provided the lowest water flow through the joint. According to the literature this is due to the better adhesive strength of the latex and the presence of the crystalline admixture.

5. DISCUSSION

The laboratory trials carried out using C+PL modified mix indicated that a watertight single shell lining can be considered achievable.

The literature also identified that a polymer modified mix is suitable to construct watertight sprayed concrete tunnels linings. According to Ohama, Y et.al (1987) latex modification for SBR latexes happens in two processes: cement hydration followed by latex film formation. In surfaces where there is loss of water due to evaporation, the film formation will be faster than cement hydration. In a polymer cement mix system, as water is lost due to evaporation and cement hydration, polymer spheres approach each other and eventually touch and fuse into a continuous film. According to Ramakrishnan et al (1992) the polymer film sealing effect provides enhanced watertightness, resistance to moisture, chemical resistance and durability. These authors also added that polymer particles coalesce to form a continuous close-packed layer on the cement gel and aggregates. This will improve the interparticle bonds as well as the strength and toughness of the concrete. According to the literature, the polymer modified concrete results in the development of a latex binder throughout the mix and this imparts increased bond, flexural and tensile strength and improved ductility and toughness (Ramakrishnan et al 1992).

Polymer latex in combination with crystalline admixtures has a beneficial impact on water penetration, water absorption and shrinkage. Also, the rheometer data indicates that the amount of water or superplasticiser could be reduced in the mix with the addition of PL. Reducing the w/c ratio for this mix increases the yield stress to a value closer to the target value. It may also result in a higher viscosity; this could be advantageous to minimise the rebound in spraying, provided that the mix would be pumpable. Another advantage of using the C+PL modified mix is that unlike normal sprayed concrete, higher strength would be achieved by dry curing at ambient temperature and humidity, allowing any excess water to evaporate and the formation of the latex film in the internal structure, which improves the properties of sprayed concrete.

The Modulus of elasticity of the mix is an important parameter for the SCL design. This test has not been carried out during this laboratory trial. However, the tests carried out by Ohama, Y et.al 1978 with the SBR modified concrete mixes indicated that the modulus of the mix is depends on the polymer/cement ratio. The results indicated an increase in the stiffness between 6 to 12% for the samples tested with 5 to 20% polymer-cement ratio.

Based on the results of the laboratory trials and the literature review, the C+PL modified mix can be used to construct a watertight sprayed concrete tunnel lining. Further optimization and testing of this process with varying amount of polymer/cement ratio should be carried out through site trials.

Staggering the position of the joint in successive SCL layers is a common approach to improve watertightness. Where there is a higher risk of water ingress then it may be possible to spray in two layers separated by a fibre reinforced C+PL modified layer, as shown schematically in Figure 10. This combination of staggered joints separated by a ‘waterproof’ layer would both extend and potentially block the water path. The Layers 1 & 2 combined would be the primary lining. The layer 3 would be a minimum thickness required mainly for the fire protection purposes. Typical thickness of the layers for SSL are shown in Table 7.

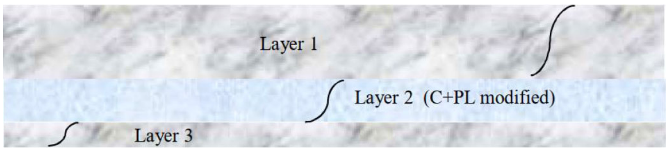

Figure 10 : Typical application of SSL arrangement

It should be noted that the Crossrail Project (UK) proposed thicknesses for a typical soft ground 10m sprayed concrete lined tunnel is 794mm (Thomas, A & Dimmock, R 2017). This includes 4mm membrane thickness, 40mm regulating layer and 300mm secondary layer. By adopting the configuration proposed in Figure 10 a watertight single shell lining can be constructed to a maximum thickness of 450 mm (Table 7). This would result in at least 43% reduction in lining thickness.

Table 7: Layers and proposed thicknesses for a typical soft ground 10m SCL tunnel

	Layers	Proposed SSL	Crossrail*
1	Sealing Layer	50*	75
2	Primary Layer	325 (layers 1 &2)	325
3	Regulating Layer	0	40
4	Membrane	0	4
5	Secondary Layer	0	300
6	Fire protection layer	75* (layer 3)	50
	Total	450	794

* After Thomas, A & Dimmock, R 2017

The following advantages are being expected by using the proposed single shell lining arrangements:

- Economic and sustainable lining design through both reduced excavation and lining thicknesses.
- Unlike sheet or spray membrane no specialised requirement for skilled workmanship with qualification testing, supervision and quality assurance to ensure an effective installation.

- No need for a regulating layer; the C+PL modified mix can be applied on complex geometries, wet and rough surfaces.
- Better bonding, low absorption and watertight characteristics of the mix provide durability benefits for the concrete and the steel reinforcing bar used at junctions.
- Enhanced constructability due to ease of application, giving both productivity and safety benefits for tunnel construction. Significant saving on the cost and the time to install the lining by eliminating the waterproof membrane.

5. CONCLUSIONS

The watertightness is an important performance requirement for many sprayed concrete tunnel linings. Failure to achieve a required level of watertightness could impact on construction cost, program and the future maintenance and the amenity value of the tunnels.

According to the calculations using the Valenta equation, it is possible to have a 300 mm, single shell watertight sprayed concrete lining, with a design life of 120 years, subjected to a pressure head of 50m, provided that the average hydraulic conductivity of the lining and the joints is around 5×10^{-14} m/s.

Hydrophobic, Pore blocking admixtures also reduce shrinkage and water penetration but are not effective at controlling water penetration at construction joints. Due to its water repelling effect the Hydrophobic modified mix denies the hydration across the joints.

The tests indicate that mixes containing crystalline and polymer latex have reduced water penetration, shrinkage and water absorption compared to the control. However, the polymer latex interferes with hydration leading to lower early compressive strength. This may be mitigated by increasing the accelerator dosage.

Similar values of water penetration for jointed and non-jointed samples for the crystalline modified admixture sample indicates that the standard water penetration test (72 hours water pressure application) would not be enough to see the effectiveness of the crystalline admixture and therefore a longer duration test would be beneficial. The longer duration test carried out continuously for 28 days show the effectiveness of the crystalline admixture in controlling the water ingress through joints. The same tests confirmed that C+PL is the best admixture for reducing water penetration at joints.

Building on the acceptance of the use of sprayed concrete for the permanent tunnel lining, the Single Shell Lining approach with the C+PL modified mix with staggered layers provides the possibility of achieving an efficient watertight lining by controlling water ingress, cost and sustainability.

6. ACKNOWLEDGEMENTS

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