Design & construction of Mumbai Metro Line 3 Sahar Road crossover cavern using permanent sprayed concrete linings

A. Bedi[1], S.K. Gupta[2], S.Trivedi[2] and A. Pengelly[3]
[1]Bedi Consulting Ltd. London, United Kingdom
Mumbai Metro Rail Corporation[2], Mumbai, India
[3]Normet, India, Pvt Ltd.
E-mail: a.bedi@bediconsulting.com

ABSTRACT: The Sahar Road Crossover Cavern (SRCC) is a stepped profile cavern on the Mumbai Metro Line 3 project, and comprises 6no. different cross sections, symmetrical about the middle of the cavern. The original design called for a conventionally reinforced, cast-in-situ secondary lining, though given the number of geometrical sections and complexity of staging the works, Mumbai Metro Rail Corporation opted to explore the use of sprayed waterproofing membranes and permanent fibre reinforced sprayed concrete linings (PSCL) as well as development of a 'drained regulating layer' concept which allowed the application of sprayed waterproofing membranes in wet conditions; this is a first for any metro project in India, with the latter considered an international first. The successful implementation of water-management and PSCL linings on the SRCC is envisaged to be a revolutionary step forward for the tunnelling industry in India

KEYWORDS: Permanent sprayed concrete lining (PSCL), fibre reinforced sprayed concrete (FRSC), Mumbai Metro, India

1. INTRODUCTION

Mumbai is a coastal, tropical city with high groundwater levels that are affected by the annual monsoon. The fractured igneous rocks make for a stable tunnelling medium, though management of groundwater inflow is a key challenge. The metro tunnels are designed as tanked structures in the long term, and so to fulfil a 120 year design life, durability of the waterproofing membrane and fibre reinforced sprayed concrete (FRSC) secondary lining was a key challenge. The objective of this paper is to discuss the challenges faced and how they were overcome to successfully deliver this within India for the first time.

The locally available sand and aggregates in Mumbai are inherently variable and considered poor quality for the application of permanent sprayed concrete linings. Furthermore, local design standards do not provide the required governance needed to implement PSCL that would achieve 120 year design life. Therefore, it was necessary to develop a bespoke Materials and Workmanship (M&W) specification for the project according to British Standards (BS) and European Norms (EN). This M&W spec would form the basis review and test all the available local materials and testing labs to ensure consistent quality for the duration of the project.

Previous projects such as Crossrail in the UK (Batty et al., 2016) faced numerous issues with bonding and curing of spray applied waterproofing membranes on damp and seeping primary linings. The Crossrail project was constructed in relatively impermeable London Clay, and given the permeability of the fractured rock mass at the SRCC location, it was expected that significant water ingress through the primary lining would be inevitable after its construction. Achieving a relatively dry primary lining substrate was a key factor in assuring successful installation of the sprayed waterproofing. Hence, a detailed water management approach was developed specifically for this project, alongside another water management M&W specification. This is considered an international first, and its development is described herein.

Due to concerns on the aggressive groundwater and the quality of the spraying, the primary lining is designed as temporary works and is assumed in the design to degrade in the long-term. The final design solution adopted is shown in Figure 1 below and consists of a new concept of an 'engineered drained regulating layer' to manage groundwater inflow in the temporary case. A fibre-reinforced arch with a conventionally reinforced concrete base and sheet membrane are adopted for the invert, as shown in the figure below. Figure 2 shows the details of the final arrangement. The whole crossover was divided into six typical segments (A to F). These six segments differ in length and cross section. The crossover structure has a total length of approx. 227 m, with spans ranging from 7m to over 20m.

This paper presents the results cavern design and implementation on site. Details of the mix design developed using locally sourced materials, and its performance are also presented. The paper draws conclusions on the various lessons learned during the design and construction of this cavern. Recommendations for future projects and avenues of potential improvement.

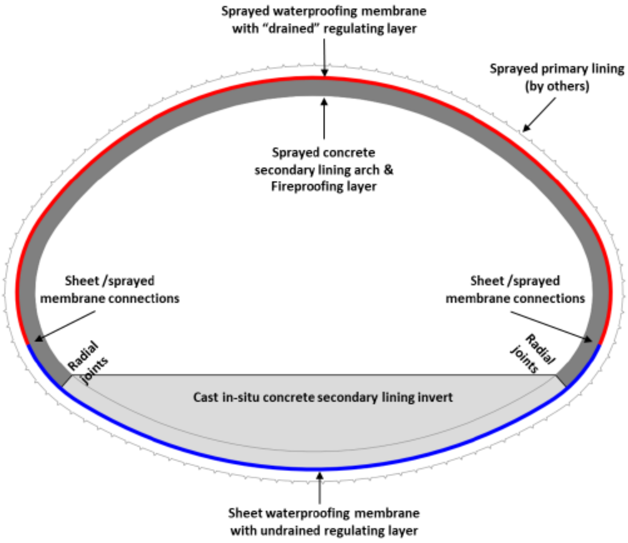

Figure 1 Design configuration of SRCC waterproofing and FRSC

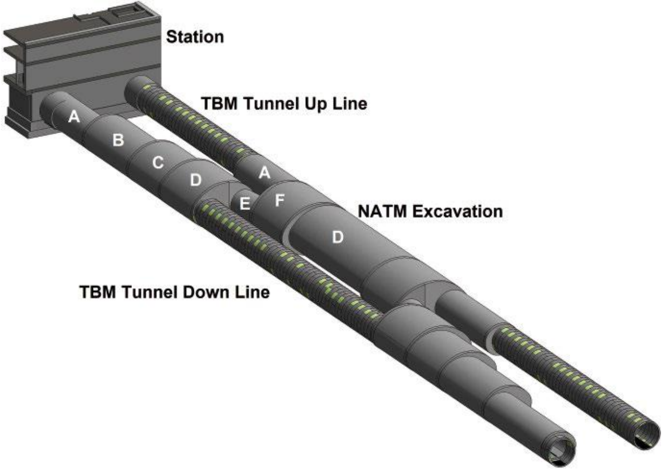

Figure 2 Stepped arrangement of SRCC sections

2. DESIGN CONCEPT

2.1 Design Loading

The FRSC secondary lining was designed and checked for all possible combinations of applied loads and forces in accordance with the Mumbai Metro Rail Corporation (MMRC) Ordinary Design Standard (ODS). This sets out the performance criteria for all civil engineering structures on the project, for the following stages:

1. Short-term (during construction)
2. Intermediate (immediately after construction)
3. Long-term (full design life) loading conditions
4. Accidental: These include unusual incidents which may alter loading conditions. For the SRCC, these included loads arising from train derailment and fire.
5. Extreme: Those that occur in service/operation when groundwater may rise to unusually high level.

Given the central urban environment, variable water table heights, seismic zone and propensity of future development, various loads and combinations were considered (see Table 1). The ODS also required the PSCL secondary lining to be designed for full overburden.

Table 1 Loads considered in PSCL design

Type	**Action**
Permanent actions (G)	Self-weight
	Dead loads
	Earth pressure – Full overburden in long term
	Maximum groundwater pressure during construction
	Minimum groundwater pressure
	Long term groundwater pressure (normal operations)
	Extreme groundwater pressure (long term only)
	Shrinkage and thermal effects
Variable actions (Q)	Short term construction surcharge – 20kPa
	Long term oversight development surcharge – 50kPa
	Oversight development excavation – up to 3m deep
Seismic actions (EQ)	Vertical and Horizontal ground accelerations due to earthquake

Of particular note, the groundwater level in Mumbai is seasonal, with flooding common during the monsoon season and significantly lower groundwater levels observed in piezometers installed prior to construction (see Table 2).

As such, the lining design was not necessarily governed by any one particular load case, and parametric analyses were undertaken to determine the design thickness of the PSCL secondary linings. These ranged between 300mm for the smaller sections (A & E in Figure 2) and 450mm for the larger sections (E & F in Figure 2).

Table 2 Design groundwater scenarios

Design scenario		**Ground water level**
Short term (during construction)	No groundwater acting on secondary lining. Ground water channelled to tunnel invert through drained regulating layer	At tunnel invert
Intermediate (immediately after construction)	Measured maximum plus 1.5m	2.0m below ground level + 1.5m (i.e. 0.5m BGL)
Service/Operation	1 in 50 years return period plus 1.0 m	Ground level + 1.0m
Extreme	1 in 50 years return period plus 2.0 m	Ground level + 2.0m
Minimum GWL	Drawn down during construction	Ground water at tunnel invert (drained tunnel)
	Actual water level minus 3m	Ground level - 7.5m (Lowest measured 4.50m below ground level)

2.2 Excavation, initial support and primary lining

As shown in Figure 3, the strata in which the SRCC was excavated comprised moderately weathered (Grade-III) Breccia with slightly weathered (Grade-II) Basalt in the invert. Four major sets of joints, including a bedding plane, are prevalent in the rock mass, which coupled with the high water table, meant that significant water inflow was expected through the rock mass. Water pressures were alleviated by allowing drainage through the primary lining, and into a temporary sump during excavation.

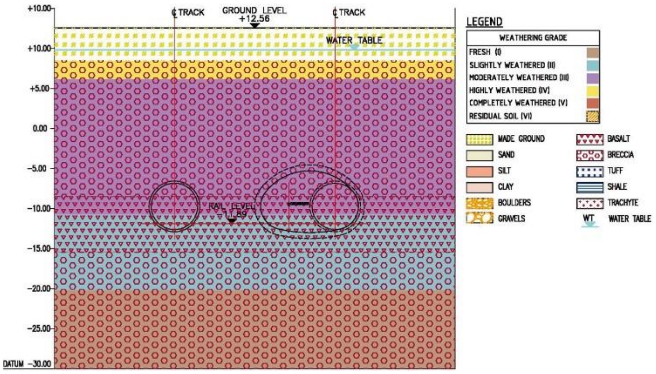

Figure 3 Stratigraphy and ground conditions at SRCC (Panwar et al., 2020)

2.3 Secondary lining design configuration

As mentioned above, the primary rock support and lining elements were considered temporary, and so not included in the structural design for the secondary lining and long-term loading, which was designed for the worst case of over-burden and hydrostatic load cases presented earlier. Based on the analyses undertaken, the cavern lining design was split into two distinct components:

(1) Cast in Place (CIP) conventionally reinforced invert, and;

(2) Fibre reinforced sprayed concrete (FRSC) arch.

The arch consists of a drained regulating layer, a sprayed waterproofing membrane, a fibre-reinforced sprayed concrete secondary lining, and a final fireproofing layer, as shown in Figure 4.

Figure 5 shows the configuration of the invert that comprises an undrained regulating layer, a waterproofing system composed of a sheet membrane and geotextile fleece, and a conventional steel bar reinforced CIP secondary lining concrete layer.

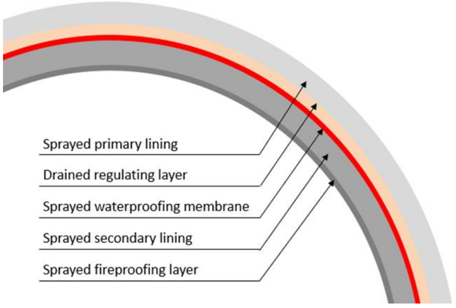

Figure 4 FRSC arch lining configuration

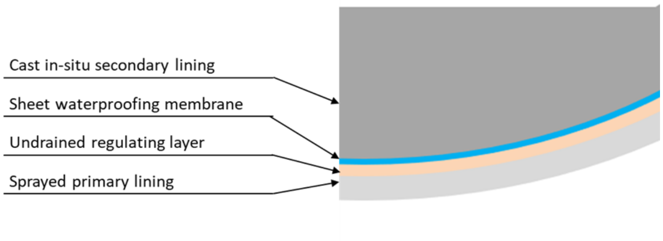

Figure 5 CIP invert configuration

2.4 Secondary lining construction sequence and assumptions

Given the groundwater inflow through the rock mass and primary lining, a sequential approach to construction of the waterproofing system was developed. The main objectives of this structured construction sequence were to avoid problems experienced by projects such as Crossrail, where water percolating through the primary lining meant that sprayed membranes did not cure sufficiently, or took excessive time to cure and required multiple repairs. Thus the objectives of the construction sequence developed were as follows:

(1) Actively manage all water flowing through the primary lining and positively direct this to the temporary drainage in the invert. This would reduce injection grouting to areas only where strictly necessary.

(2) Provide a dry substrate through a drained regulating layer on to which the sprayed membrane could be applied and allowed to cure.

(3) Alleviate groundwater pressures on the waterproofing membranes and CIP invert until the full structural lining was installed and gained full design strength.

2.4.1 Stage 1 – Invert construction

Figure 6 shows the configuration of the lining at this stage, with the key design assumptions as follows:

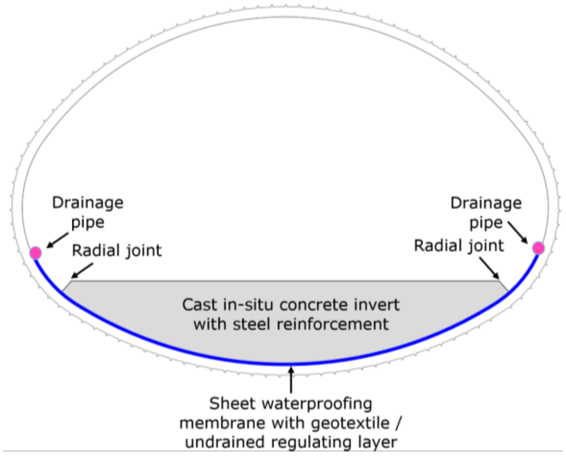

Figure 6 Stage 1, invert construction

- Drained tunnel, no water pressures acting on tunnel lining
- Ground loads carried by primary lining
- PVC sheet membrane installed with drainage below to allow seepage to be channelled to temporary sumps.
- CIP concrete invert placed and allowed to gain full design strength in compliance with M&W specification.
- Regulating layer designed as temporary structure to protect invert from any stray fibres or sharp undulations from piercing the PVC membrane.

2.4.2 Stage 2 – Arch waterproofing

Figure 7 shows the configuration of the lining at this stage, with the key design assumptions as follows:

- Drained tunnel, no water pressures acting on tunnel lining
- Ground loads carried by primary lining
- Drainage mat and regulating layer create drainage channel for ingress water to be diverted to drainage pipes at “knee”
- Drained regulating layer creates dry substrate for the sprayed membrane
- Drainage mat installation in compliance with suppliers’ recommendations
- Drainage pipe installation in compliance with supplier’s recommendations
- All water management measures channel water into the invert drainage and provide a dry substrate for sprayed membrane application.
- Sprayed membrane applied on dry substrate in compliance with Materials & Workmanship Specification and its application in compliance with supplier’s recommendation

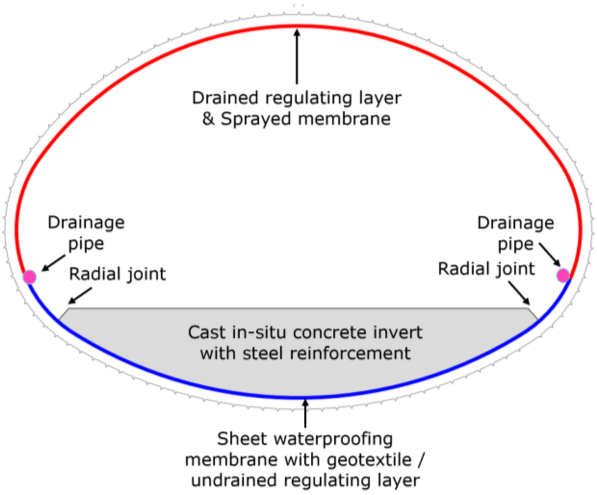

Figure 7 Stage 2, arch waterproofing

2.4.3 Stage 3 – Arch secondary lining and fireproofing

Figure 8 shows the configuration of the lining at this stage, with the key design assumptions as follows:

- Drained tunnel, no water pressures acting on tunnel lining
- Ground loads carried by primary lining
- Spray secondary lining concrete & fireproofing layer
- All water-management remains active and no water pressures allowed on secondary lining.
- FRSC applied in compliance with Materials & Workmanship Specification
- Moist curing of the secondary lining to limit cracking in accordance with the ODS (0.2mm at intrados and 0.3mm at extrados)
- Fireproofing layer in compliance with fireproofing layer Materials & Workmanship Specification

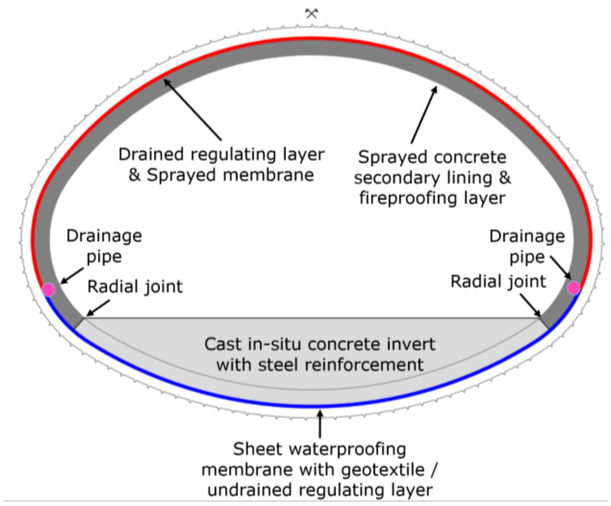

Figure 8 Stage 3, arch secondary lining

2.4.4 Stage 4 – Tanked tunnel for long-term condition

At this stage, all temporary water-management installed (shown earlier in Figure 8) is back grouted tight and temporary sumps filled with concrete and waterproofing applied over. The key design assumptions are as follows:

- Fully tanked 'undrained' tunnel
- Groundwater loads on secondary lining
- Ground loads on secondary lining
- Secondary lining and fireproofing layer durability in compliance with Materials & Workmanship Specification.

2.5 Water-management

The sprayed waterproofing membrane adopted for the SRCC was the TamSeal 800 Ethylene-Vinyl-Acetate (EVA), which is the same as that used on projects such as Crossrail in the UK (Batty et al., 2016). The main limitation of the EVA membrane is that it cures and bonds to the substrate on which it is applied by the evaporation of water. As such, a damp substrate coupled with the relatively high humidity of the Mumbai air meant a bespoke solution needed to be developed, which would allow a dry regulating layer on to which the EVA membrane could be applied.

To systematically manage groundwater ingress and limit the amount of injection grouting required – which could potentially just push water to a different location in the cavern – 4no. water ingress classes were defined (see top table in Figure 12, below) with a water management strategy (see lower flowchart in Figure 12, below) to achieve a suitable substrate for application of the sprayed waterproofing membrane. The water management was then covered by a regulating layer, which together were termed the 'drained regulating layer'. Figure 9 shows various measures that were developed and applied around the cavern to channel water ingress, based on the assessed water ingress classification.

2.5.1 Drained regulating layer

The drained regulating layer consisted of drainage mats and strips, where required, directly installed onto the primary lining and covered with a layer of finer aggregate sprayed concrete.

The drainage mats or strips were installed directly onto the intrados of the cavern primary lining. The main purpose of this drainage was to provide a flow path for any leakage towards the invert drainage.

Once the drainage elements were fixed, a layer of finer aggregate concrete of nominal 50mm thickness was be sprayed onto them and the intrados of the primary lining. The purpose of this layer is to provide a closed water path for any water seepage through the primary lining, as well as a smooth and dry substrate for the spray of waterproofing membrane. This layer was sprayed using a dry mix sprayed concrete.

In the design, both the regulating layer and the drainage elements were considered as temporary and non-structural elements in the long-term.

Figure 10 shows the typical temporary drainage detail underneath the PVC sheet membrane, which channelled all seepage to the temporary sumps. Figure 11 shows the termination detail developed between the invert and arch to allow positive drainage in the temporary case, until Stage 4 where the temporary elements were grouted up and water pressures allowed to develop on the secondary lining.

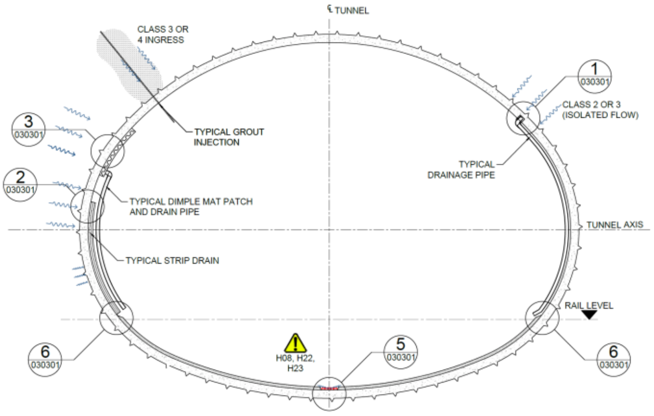

Figure 9 Schematic of typical water management measures

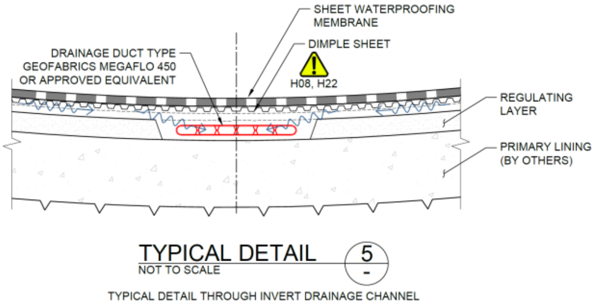

Figure 10 Invert temporary drainage detail to direct all seepage to temporary sumps

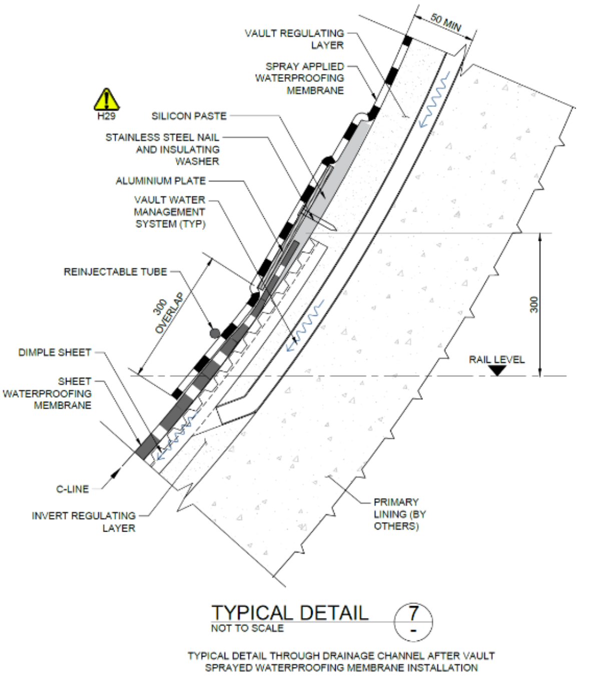

Figure 11 Sheet/sprayed membrane termination detail

Water ingress class	Water Ingress Observed	Management Solution	Products to be used
Class 1	Damp patches (no running water observed)	No action required	None
Class 2	Trickling or seeping water through undefined localised imperfection of lining	Targeted chemical grout injection via systematic or local packer installation in sprayed concrete lining	Low viscosity (<20mPa.s) acrylic injection gel
Class 3	Steady stream of water ingress through visible cracks or construction joints	Systematic chemical injection through staggered injection packers into sprayed concrete lining	Flexible polyurethane grouts with reaction times to allow penetration into cracks and joints
Class 4	Localised significant water ingress through lining imperfections	Target deep drilled injection holes through lining into groundmass with chemical injection, or the use of water bleed pipes fed into back of invert PVC sheet membrane	Water stopping hydrophobic polyurethane grouts that use separate catalyst to control reactivity for the given situation Plastic bleeder pipes drilled and grouted into centre of water ingress areas. Max dia. 20mm. Fixed to lining at 0.5m max centres

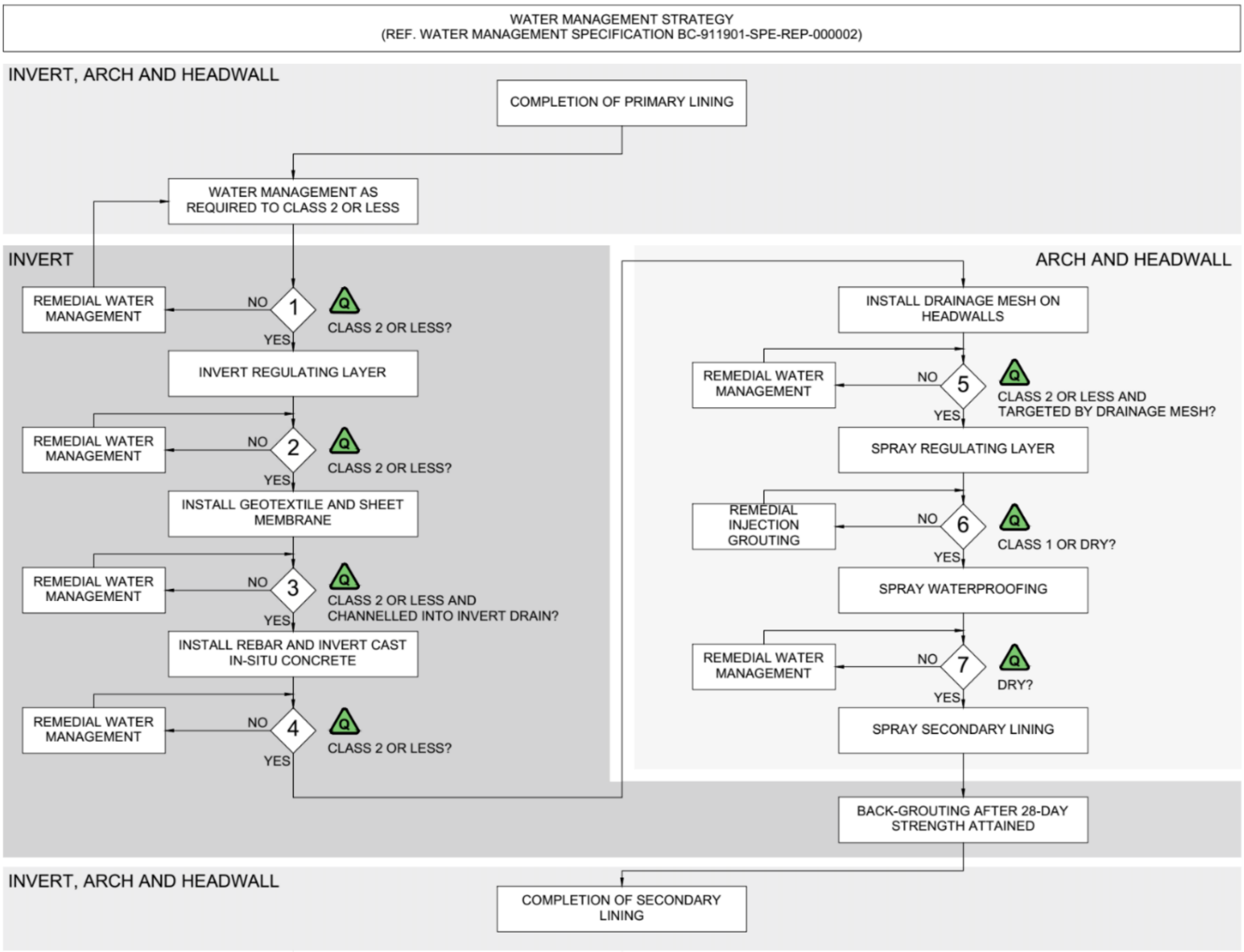

Figure 12 Water management classes and site processes implemented

3. MATERIAL SPECIFICATION AND SELECTION

The key design requirement of the project Outline Design Specifications (ODS) was for the structure to be durable for a 120 year design life. This presented an immense challenge given the variability in the local materials as well as local standards and testing laboratories not being set up for the design and assurance of permanent FRSC.

3.1 Waterproofing

3.1.1 Sheet membrane and invert drainage

Standard 2.0mm thick PVC sheet membrane was specified in the invert with geotextile fleece and dimple sheet so that water could drain freely behind this and then longitudinally into a temporary sump

3.1.2 Sprayed waterproofing membrane

The sprayed waterproofing membrane was designed to be bonded to the drained regulating layer and primary lining so that any inflow through it would be localised by the adjacent bonded membrane, and local spots could be dealt with through various means mentioned earlier.

The key performance parameters specified were as follows:

- Thickness = > 3mm total thickness (2mm wet film each layer)

- Bond to substrate = Failure shown to be in substrate or bond > 0.5MPa
- Water permeability = Zero penetration of water through the membrane
- Crack-bridging = Class A5 (@20°C)

3.2 Permanent sprayed concrete secondary lining

To achieve the required durability and water-tightness, the key performance parameters specified for the FRSC secondary lining were as follows:

- Water permeability (chemical durability) < 25mm penetration
- Density >2250kg/m3
- Crack width < 0.2mm at the extrados and <0.3mm at the intrados
- Concrete shrinkage was limited to less than 0.03% at 28 days

3.2.1 Grading and particle size distribution

The quality of sand and aggregates in Mumbai are well known for their variability and poor quality. It was therefore necessary to review and test all the available local sources according to EN standards as stated in the developed M&W specifications to ensure consistent quality for the duration of the project. Sand quality is even more important with respect to sprayed concrete, in particular for the purpose of permanent linings, because it effects many parameters in both the wet and dry states. Of particular concern were the high degree of silt and dust contents in the local sand available in Mumbai.

Figure 13 shows the initial best local combined grading curve that could be obtained using existing sources and manufacturing processes. The high silt/clay content in the local sand resulted in reduction in binding capacity of mixed material and ultimately results in less compressive strength, density, durability and workability.

Consequently, the local teams worked closely with the chosen local aggregate suppliers to provide a sand that fitted the specification requirements by adjusting sieve sizes and washing the sand to provide a bespoke product to the project. The use of microsilica was specified in the SRCC M&W Specification, and added to the mix to maintain a sufficient paste content in addition to a minimum cement content of 475kg/m3. The resulting combined grading curve shown also overlain in Figure 13.

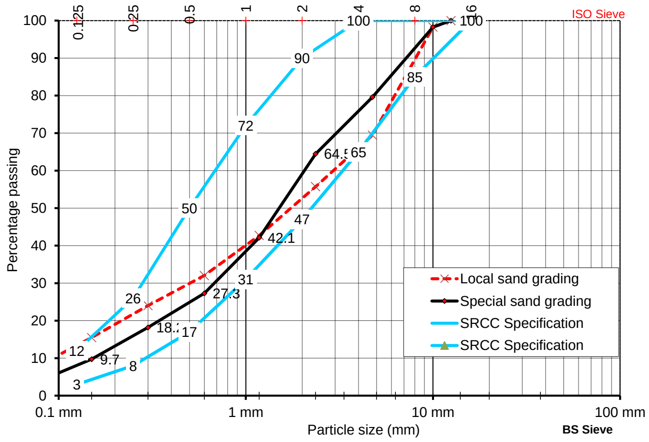

Figure 13 Grading curve with local and special sands

These additions implemented for the SRCC avoided issues with segregation and also ensured the optimal sprayability, early strength and structure/surface. Tests were also conducted to replace cement and microsilica with Fly ash and GGBS but in the spray trials it was observed that this impacted early strength requirements negatively (and hence safety) due its incompatibility with the local cements.

A further challenge was the requirement of a 5 hour retention time of the wet mix, as the batching plant was 11km away from the site, in 30+ degrees temperatures with heavy traffic conditions. In addition, the concrete needed to be transported via slickline down to a transit mixer in the tunnel which carried the concrete to the spray robot.

A formulated product (TamCem HCA) was added which prevented the hydration of cement for a prescribed time, without impact on the early strength development of the concrete. The use of conventional retarders were not an option as this had detrimental impacts on early age strength.

3.2.2 Structural specification

The design specification required early age strength of J2 (BS EN 14487), with the 28 day compressive strength > C32/40 and C40/50 at 90 days. The main driver for the strength requirements was to allow the use of FRSC only, and safe application of the SCL given the relatively thick sections (up to 450mm) and large spans (ca. 20m).

Numerous pre-construction tests were conducted with different mix designs, admixtures and accelerators in order to check the interaction of their chemistries with the local cement. Some trial J2 curves are attached in the Figure 14 to Figure 17 below. The best combination was using the mix design with ‘TamShot 90AF’ (Normet) accelerator, ‘TamCem 60’ admixture (Normet), TamCem HCA (Normet) and TamCem microsilica (Normet). Other graphs demonstrate considerable sleeping periods which risked drop outs from the shotcrete and compromise the safety of the sprayed concrete up to 3 to 5 hours.

The FRSC was specified to achieve a residual flexural strength class of D3 S2.5 in accordance with BS EN 14487-1 and tested using 4-point beams cut from sprayed panels in accordance with BS EN 14488-3. The mix was dosed with 38 kg/m3 of Dramix 4D fibres, and a local testing laboratory was set up by Normet at their facility in Jaipur.

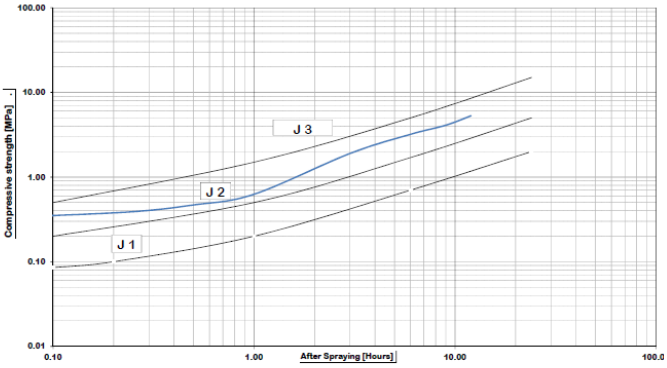

Figure 14 J2 curve using Tamshot 90AF, OPC + microsilica

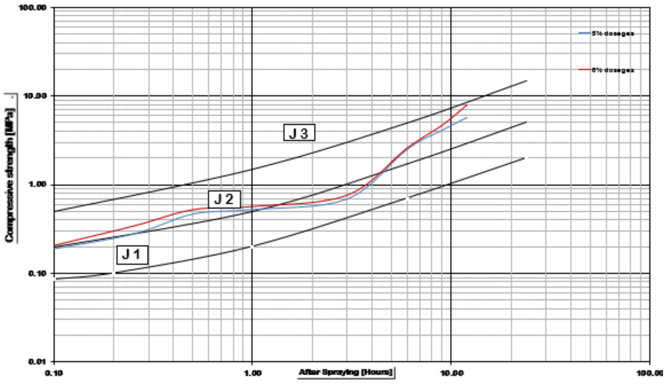

Figure 15 J2 curve using Tamshot 90AF and OPC

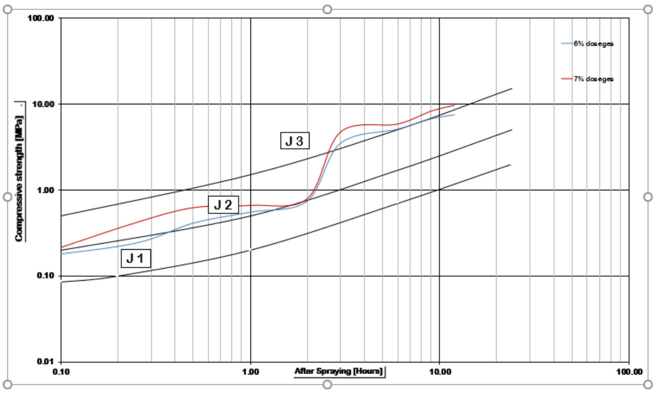

Figure 16 J2 Curve using conventional retarder, cement + Microsilica & 90AF mix.

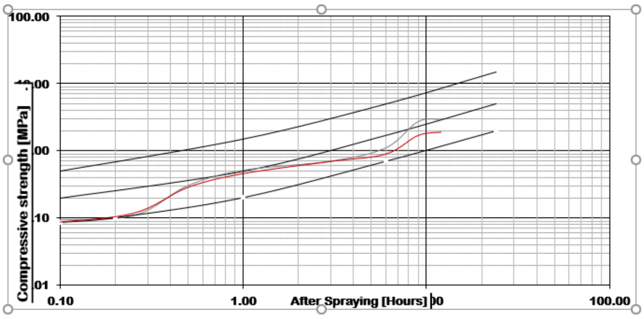

Figure 17 J2 Curve using 90AF, Cement+ Fly ash mix

4. CAVERN CONSTRUCTION

The SRCC was successfully constructed to the design requirements and M&W specifications described herein. The following section presents some of the key challenges and pictures at major stage throughout construction of the secondary lining.

4.1 Invert construction

This stage was a critical step as seepage would need to be channelled below the invert and longitudinally along the cavern in to the temporary sump.

Preparation of the invert longitudinal drainage and spraying of the regulating layer on it (Figure 18) was pivotal providing a smooth surface of the upper drainage elements shown earlier in Figure 10. These elements would carry a large amount of water over that was collected from the numerous seepages along the length of the cavern.

After the regulating layer was sprayed and drainage layer and fleece (Figure 19), after which the sheet membrane and termination details were constructed, as shown in Figure 20, in preparation of the arch drained regulating layer.

4.2 Drained regulating layer

The other decisive stage in success of the FRSC lining was management of the arch water ingress and channelling this in to the constructed invert drainage. The protocols set out earlier in Figure 12 were methodically followed and recorded in checksheets, with the relevant assurance inspections and hold points released before each next step.

Figure 21 shows typical temporary drainage elements being installed in areas pre-marked out, with grout injection points specified as well. Only once all water seepage was successfully controlled to below Class 2 was the hold point to spray the regulating shotcrete released. Figure 22 show invert/arch joint with all water management installed and the termination detail ready to be installed prior to the sprayed waterproofing membrane.

Figure 18 Primary lining complete. Invert drainage and temporary sump construction

Figure 19 Invert under-membrane water management installation

Figure 20 Invert temporary water management and drainage collection

Figure 21 Installation of water management details prior to spraying

Figure 22 Invert/arch waterproofing termination construction

4.3 Sprayed waterproofing membrane

The sprayed membrane application was very successful (Figure 23) due to the robust water management processed developed and implemented on site. Some local repairs were required at very local points of residual water ingress after the sprayed membrane application, though these were limited to a few local drips throughout the length of the cavern.

Figure 23 Sprayed waterproofing membrane 2nd pass complete

4.4 FRSC Secondary lining construction

Figure 24 shows the completed FRSC secondary lining within the cavern. No specific issues were encountered during construction of the secondary lining. The FRSC was checked through ongoing production trials for strength, density, residual flexural strength and water permeability during construction.

5. CONCLUSION

The SRCC was successfully constructed using a FRSC permanent secondary lining. This was a first in India for any metro project.

As a first in India, one of the primary challenges was developing a high quality mix design that would meet all the strength and 120 year durability requirements of the clients specification using locally available sand and aggregates in Mumbai, which are inherently variable and considered poor quality for the application of permanent sprayed concrete linings. The project team thus developed a bespoke Materials and Workmanship specification for the project according to British Standards (BS) and European Norms (EN). This M&W spec would form the basis review and test all the available local materials and testing labs to ensure consistent quality for the duration of the project. The site team sourced and engineered the local materials and mix to conform to these stringent requirements.

Figure 24 FRSC lining complete

Secondly, given the fractured nature of the rock mass, significant water ingress was expected through the primary lining, which, if not managed, would not allow the sprayed secondary lining to cure. This problem had lead to slow production and re-work on previous projects such as London’s Crossrail. The project team developed a detailed water management approach specifically for this project, alongside another water management M&W specification tailored to the humid conditions in Mumbai. The concept of an engineered drained regulating layer was developed on this project to achieve a suitable substrate for application of the sprayed membrane. This is considered an international first, and the experiences from Mumbai may help to form a benchmark for future projects faced with similar challenges.

6. REFERENCES

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