Review of the ITA Report on Permanent Sprayed Concrete Lining

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The Working Group 12 (WG12) of the International Tunnelling and Underground Space Association (ITA) on sprayed concrete use has published reports for almost three decades showing the advantages of using sprayed concrete for permanent lining of tunnels. The first illustrated the state of the art in 15 countries (Franzén, 1993). The main idea behind the reports has been to show how reliable sprayed concrete can be for that purpose. In 2020, the Working Group joined efforts with the ITAtech Activity Group on sprayed concrete and produced the report 'Permanent Sprayed Concrete Linings' (ITA, 2020). This review will focus on the 2020 report, hereafter referred to as the Report.

All the reports have highlighted recent technological advancements in the production and placement of sprayed concrete. However, none of them has claimed to be an exhaustive source of information about these latest technological developments. They have not necessarily been the basis for the decision of adopting permanent sprayed concrete lining (PSCL) which should depend on demonstrating the reliability, durability, and viability of the solution. The reports have also compiled a significant number of international case histories from important underground infrastructure works which have adopted PSCL. Information from ITA Member Nations has been of great value. Important contributions have also come from the members of the Working and Activity Groups in charge of producing the reports, many of whom have used their expertise during the decision processes for adopting the PSCL solution.

Despite not containing all the latest technological developments on sprayed concrete, the reports have been effective in producing information used in the decision for the adoption of PSCL for some sensitive underground works. A good example is the 200m² cross section, 4-lane twin tunnels which carry more than 80 thousand vehicles per day on the Western section of the São Paulo Ring Road. The original design called for cast in situ concrete for the permanent lining. The occurrence of excessive overbreak during excavation led to contractual litigations as the volume of concrete would be significantly higher than that anticipated in the bidding documents. The adoption of sprayed concrete for permanent lining (Celestino et al., 2006) resulted in lower costs, shorter construction times and no litigation. That decision was taken in 2000. Reference to the previously published ITA reports on PSCL was essential for that decision process. This Report is too recent to have already generated similar positive impacts but certainly that will be the case. As clearly stated in its objective, it is intended "... to give owners and their advisors the confidence to incorporate PSCL in their underground space design", and "... to inspire and inform so that more projects can take advantage of this technology".

Among the new aspects covered by the Report, the topic related to carbon footprints of construction deserves to be mentioned. This is a growing concern for society, as well as an aspect more and more frequently mentioned in requirements of recent bidding processes. It will be a factor in favor of the PSCL solution in new projects which will deserve more attention in future ITA reports, as mentioned later in this review.

Service lifetime and durability

Perhaps the aspect which raises most uncertainty about the use of PSCL is related to service lifetime and durability. All underground works which have adopted PSCL in the past and which still perform well should be used as good examples for the evaluation of lower limits of sprayed concrete durability. Improvements in materials and placement technologies, as well as lessons learned from the occurrence of the corrosion of steel mesh and lattice girders and other problems, if well used and interpreted, are good indications that future projects will perform even better. A suggestion for future reports is to present what has happened to many of the projects shown in compilations of previous reports, in terms of maintenance needs and durability. It is known that many tunnels and caverns constructed more than 40 years ago which have adopted PSCL have performed well, but a quantitative and assertive statement about this fact depends on a rational survey of their current condition and maintenance record. Since the placement method has so much influence on the final properties of the concrete, and since it has changed significantly in the past decades from manual to robotic applications, this feature must be taken into consideration in the correlations with the final quality.

A good example of investigation of the quality of sprayed concrete placed in the beginning of the 1930s as a final lining of a tailrace tunnel in an underground power plant in Sweden, after 50 years of operation, was given by Franzén (1982). That was perhaps one of the first applications of PSCL and despite the limitations of technology at such an early stage, the condition was reported to be good in the early 1980s. The adhesion to the rock substrate was measured in-situ and values higher than 1MPa were obtained. The cube strength of the concrete was indirectly estimated as 40-60MPa, based on correlations with the results of Brazilian tests on cores. The compilation of similar examples is of utmost importance.

Exposure to degrading chemical substances is well described in the Report as an important factor against concrete durability. The Report correctly suggests solutions for a denser and less permeable concrete to hinder sulphate attack. The Report also suggests the use of cement with low amounts of Tricalcium Aluminate (C_3A) as a solution to reduce the susceptibility to sulphate attack. However, as Knut Garshol has clearly stated in the Preface of the 2010 WG12 report (ITA, 2010), C_3A cements react very slowly with accelerators. Early strength, and therefore construction safety, may be compromised using such cements. Even if safety during construction is not an issue, the final quality of the concrete will be poor as it will be porous and permeable due to the incompatibility between C_3A and accelerators. A more widely accepted solution is to adopt very low water-cement ratio (lower than 0.4) and some micro silica in the mix design.

Biological attack will deserve more attention in future reports. Shirakawa et al. (2000) report the case of the attack on the sprayed concrete on an urban tunnel by bacteria and fungi nourished by diesel fuel which reached the groundwater from a gas station leakage. Both aerobic and anaerobic bacteria were found. Low pH from anaerobic bacteria were responsible for the deterioration of the concrete. To solve the problem, two acrylic resins, styrene butadiene and a silico-aluminate admixture were tested. The best results were obtained with the silico-aluminate admixture.

A possible mechanism for long-term mechanical deterioration is the potential strength loss due to the long-term action of accelerators. There is an inconsistency in the Report which must be clarified in a future version. In Section 6.3 it is stated that the latest additives and accelerators do not cause any detrimental effect on the long-term properties of the concrete. Most probably this is the case according to the reliable references cited, e.g. Thomas (2019). However in Section 14.3, describing tests to be carried out during construction, tests to check strength decrease due to accelerators are recommended. Even if that recommendation comes from standards which require the determination of the "maximum strength loss" of accelerated mixes, the Report must take an unambiguous position, even if the intention is to influence revision of such standards.

There is an inconsistency in Section 14.7 of the Report (Durability testing) with respect to the importance of the placement process. The inconsistency must be addressed in future versions of the report. It is correctly repeated throughout the Report (e.g. Sections 6.25 and 16.2) that the placement process is very important for the final quality of sprayed concrete. In Section 14.7, in an attempt to simplify testing requirements during construction, it is argued that, due to the reliability of modern computerized batching plants, the uniformity of the material produced is guaranteed to meet high level requirements. In order to capture any deviation due to the placement process, the analysis of the results of strength testing on in-situ samples is recommended. This statement is very strong and questionable as it implies that the short-term strength may be the only property that needs to be monitored.

Load on the final inner lining

One of the most controversial aspects of PSCL design is the evaluation of the load acting on the final inner lining. The process is governed by the time-dependent properties of both sprayed concrete and ground mass and on the history of the construction sequence. Theoretical frameworks based on rheological models for the sprayed concrete during the processes of strength and stiffness build up and load increase have been available (e.g. Aldrian, 1991), however, the variability of assumptions adopted in different countries is significant. It would be interesting if future reports could summarize those assumptions and their consequences in terms of total thickness of sprayed concrete for similar geometrical and geological conditions. An example of such a compilation is shown below.

Pöttler and Klapperich (1999) summarized the total thicknesses of primary plus final inner linings in single-track metro tunnels with PSCL in Germany, excavated in soft sedimentary rocks under groundwater pressures ranging from zero to 0.12MPa. The maximum overburden ranged from 6 to 19m. The total thicknesses of sprayed concrete ranged from 0.25 to 0.55m. Pöttler and Klapperich also commented that the variability of total concrete thickness is due to different design assumption. Franzén and Celestino (2002) summarized similar information for single-track tunnels excavated through stiff clays and compact sands for the São Paulo Metro under groundwater pressure up to

0.2MPa and 40m overburden. The total thickness of sprayed concrete was 0.25m. This is a clear example of lower concrete thickness under more severe conditions, confirming the importance of the design assumptions.

These assumptions vary significantly from country to country, and even between different engineering companies in the same region. They are perhaps the second most important reason, after service lifetime and durability, why PSCL is not still adopted in many countries. In this respect, it would be interesting that, in addition to Figure 2 of the Report (which is directly influenced by the total number of tunnels constructed in each region) future reports include the percentage of tunnels which have adopted PSCL in each region. For example, the very small number of only 4% in South America conveys the idea that PSCL is not well accepted in that region. The opposite is true. PSCL is indeed well accepted there. Examples are Metro running tunnels in soft ground constructed in Sao Paulo since the early 1980s, metro stations in Santiago and Rio de Janeiro, underground powerhouses etc. However, as the underground construction global market share of the region is small, Figure 2 of the Report shows only a small number.

Carbon footprints

Environmental consciousness has brought demands which have affected many activities of society. The construction industry is not an exception. The Report is the first published by ITA on PSCL to address this issue. For the benefit of the underground construction industry, it will be important that future reports include more details about this topic. The hypothetical example shown in the report is good, but the numbers shown are just a modest evaluation of what has been achieved in many real case histories.

Even though the cement content in each solution is different, a good indication about carbon footprint decrease can be taken by comparing total concrete thickness of each alternative and the decrease of excavation when adopting PSCL. In the example given in the Report, the PSCL solution reduces the total concrete thickness to 42% and the excavation span is reduced 0.36m. Taking the example of the Paulo Afonso IV underground powerhouse from the ITA (2010) report, the concrete thickness was reduced to only 10% when PSCL was adopted (from 1.50m to 0.15m), and the reduction of the excavation span reached 6.60m, 2.70m of which was directly due to the adoption of PSCL and 3.90m due to other design optimizations. Such optimizations were only possible due to the PSCL solution being adopted. Numbers like these are much more significant than the modest 20% to 50% range presented in the Report.

Dust reduction

The successful proposal of the Air Quality Working Group of the Australian Tunnelling Society to establish procedures aimed at reducing the level of dust in tunnels must be acknowledged and cited in the future version of the report. The work was the winner of the 2019 ITA Tunnelling Awards in the category 'Safety Initiative of the Year'.

The proposal is based on a set of simple principles like information sharing between major projects. On the operational side, the work went from gathering information from minor details in the tunnel, some of which proved to be important sources of dust generation like an equipment door jammed with an accumulation of dried mud. Even the interference of facial hair with a respirator that relies on correct facial fit was found to be important.

The Working Group produced a number of publications about this issue e.g. ATS (2018).

Bonding strength

The Report correctly stresses the importance of the bonding strength to the substrate (Section 6.5) and between layers of sprayed concrete (Section 10.4). In hard rock tunnels the capacity of the sprayed concrete shell to secure unstable blocks can practically disappear in a case of low bonding strength. In Section 14.1 the Report reproduces a table with recommendations of a European Standard of preconstruction tests for the formulation of the mix. In that table, tests in bond to substrate are classified as optional. It is suggested that in the next version the tests should be required.

A construction parameter highly dependent on the bonding strength is the maximum layer thickness to be sprayed at a time. The Report addresses this points a few times, but an objective criterion to define it is not provided. It is also suggested that the next version should address this point.

Spray-on membranes

Much has been learned recently about the interaction between spray-on membranes and sprayed concrete with respect to water flow mechanism. The Report only cites the most important reference (Holter, 2015) but does not go any further. It is suggested that the next version of the report should elaborate more on this topic with respect to the consequences for the mechanical properties of the membrane subject to the moisture and hygroscopic conditions.

It is also suggested that the mechanical aspect of ductility improvement of sprayed concrete linings due to the presence of the membrane should be addressed. Panel test results for post-crack assessment of specimens with and without membrane have shown significantly different results. It seems that this point deserves further attention.

Conclusion

The Report completely fulfills its objectives in terms of indicating that PSCL is a reliable and viable alternative for underground infrastructure, in addition to being advantageous in many cases. The most important recent technological developments related to materials and placement methods, which may influence design and construction of projects involving this type of permanent lining, have been addressed. Like the previous ITA publications on the same topic, the Report will have a positive impact on disseminating the advantages of PSCL in terms of cost, construction time and carbon footprints. The Report is an effective instrument to increase the viability of underground works, according to the ITA strategic plan.

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