Shotcrete And Waterproofing
For Operational Tunnels

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ABSTRACT
The paper discusses briefly the role of shotcrete and other waterproofing tools for tunnel lining. Arguments are raised in the light of ITA publications related to the subject, produced by the Association's Working Groups or in its Congress Proceedings. Since the Association reflects the opinions and the state of practice of professionals from its Member Nations, it is natural that conflicting concepts about the use of particular elements (e.g. shotcrete for final lining and waterproofing) come up in these publications. The idea of not generalizing strict waterproofing measures for all underground works alike is also highlighted for the sake of economy. Present value of maintenance costs along the service life may be lower than a higher initial cost of a maintenance-free solution.

Keywords: shotcrete, watrerproofing, tunnel, final lining.

1. INTRODUCTION

Waterproofing underground structures has been a subject of concern of many professionals for thousands of years. An ancient and interesting example is the Basilica Cistern in Istanbul, constructed in the 6th century by the Romans. At its entrance, a plate reads:

> *" The cistern is surrounded by a 4m thick wall of brick and the mortar used in constructions is very special and water-proof."*

Fifteen centuries later we are still searching for water-proof materials. Unfortunately there is no record from the Romans on how to obtain water-proof mortar. This has been an objective aimed at by many engineers involved in research, specification and construction activities, mainly for reasons related to operational aspects and durability of the works.

The interaction of underground structures with water has raised the attention of the International Tunnelling Association Working Groups (WGs), especially the WG 6 on Maintenance and Repair and the WG 12 on Shotcrete Use. Many reports and publications have been produced by those Working Groups about the subject.

Waterproofing requirements for operational reasons have become progressively stricter over the years. In the case of mass transit tunnels, the reason is the installation of more sophisticated equipment underground. Waterproofing methods have responded accordingly and the performance related to infiltration has also improved. It should be noted however that complex solutions should not be generalized for all underground works alike for the sake of economy, as long as particular operational criteria are met. In this respect, the role of shotcrete technology is very important, but its limitations should also be emphasized.

2. OPERATIONAL AND DURABILITY CRITERIA

Tunnel waterproofing is intended to meet both operational and durability criteria. Maximum infiltration rates allowed depend on the purpose of the tunnel and the owner. Criteria for mass transit tunnels are among the most demanding and usually allow for infiltration rates in the range of 1 l/m^2.day; for wastewater conveyance tunnels the allowance is usually the least demanding, in the range of 15 l/m^2.day. For sub sea highway tunnels in Norway, 14 l/m^2.day is acceptable. Those figures are not universally accepted and depend on the types of installation and equipment. For instance, a mass transit station platform requires a stricter criterion than a seldom used emergency exit.

With respect to the durability of underground structures, the ingress of water is usually the most important factor to be considered. The International Tunnelling Association (ITA) Working Group on Maintenance and Repair of Underground Structures prepared a report on the damaging effects of water on tunnels during their service life, based on case histories collected from many countries, reflecting the worldwide practices as well as different lining methods. Seventeen types of defects have been identified and specific remedial measures have been indicated. Some of the defects are intrinsic to specific lining types (e.g. segmental lining) but it can be stated that deficient waterproofing is at the origin of most problems.

A problem which has increased in urban tunnels is related to chemically aggressive ground water. For such cases, considerations of chemical interactions of pollutants with the waterproofing system are of major importance.

3. TUNNEL WATERPROOFING

Criteria for the acceptance of shotcrete as a waterproofing element for tunnels are conflicting in different countries. The idea of using shotcrete for final lining has been promoted by the International Tunnelling Association (ITA) Working Group on Shotcrete Use (Franzén et al., 2001) but it is not accepted worldwide. The working Group report proposes to evaluate the durability of a structure depending on a number of factors, including its exposure to ground water and aggressive substances.

As reported by Franzén and Celestino (2002), in another publication produced at the same Working Group, conflicting opinions about shotcrete for waterproofing exist in different countries and were clearly exposed during the 1988 ITA Congress on Tunnels and Water. While Schryer (1988) reported experiments carried out at STUVA according to which shotcrete shells should only be used in zones not more than 10m below the water table, Astad and Heimli (1988) presented information based on the Norwegian experience, according to which shotcrete can have permeability coefficient of the order of 10^{-12} m/s, therefore considered watertight for practical purposes. Among other characteristics, the use of microsilica is recommended for low porosity, and steel fibers for stress distribution and crack-arresting effects. Gomes (2005) reports results of shotcrete permeability as low as 10^{-14} m/s. In addition to the suggestions made by Astad and Heimli (1988) he also mentions the use of low hydration heat cement.

Based on back analyses of data about infiltration in tunnels with different lining systems, Celestino et al. (2001) presented the values of field permeability coefficients for those systems. The results are presented in Figure 1. The numbers obtained for shotcrete are between 10^{-11} and 10^{-8} m/s. Those tunnels were constructed at least one decade before recommendations made by Astad and Heimli (1988) an others brought significant improvement on how to obtain water-proof shotcrete. For the back analysis, permeability was calculated according to an approximate and useful expression proposed by Celestino et al. (2001), extending for lined tunnels a previous solution presented by El Tani (1999) for unlined tunnels:

$$Q = 2\pi k_g h \frac{1 - 3\left(\frac{r_{eq}}{2h}\right)^2}{\left[1 - \left(\frac{r_{eq}}{2h}\right)^2\right]\ln\frac{2h}{r_{eq}} - \left(\frac{r_{eq}}{2h}\right)^2} \qquad (1)$$

$$r_{eq} = \frac{r_e}{\left(\frac{r_e}{r_i}\right)^{kg/ke}} \qquad (2)$$

Where:

r: tunnel radius (i: internal, e: external, eq: equivalent)
h: depth of tunnel axis with respect to the water level
k_g, k_l: permeability coefficients for ground mass and lining
Q: infiltration rate per unit length of tunnel

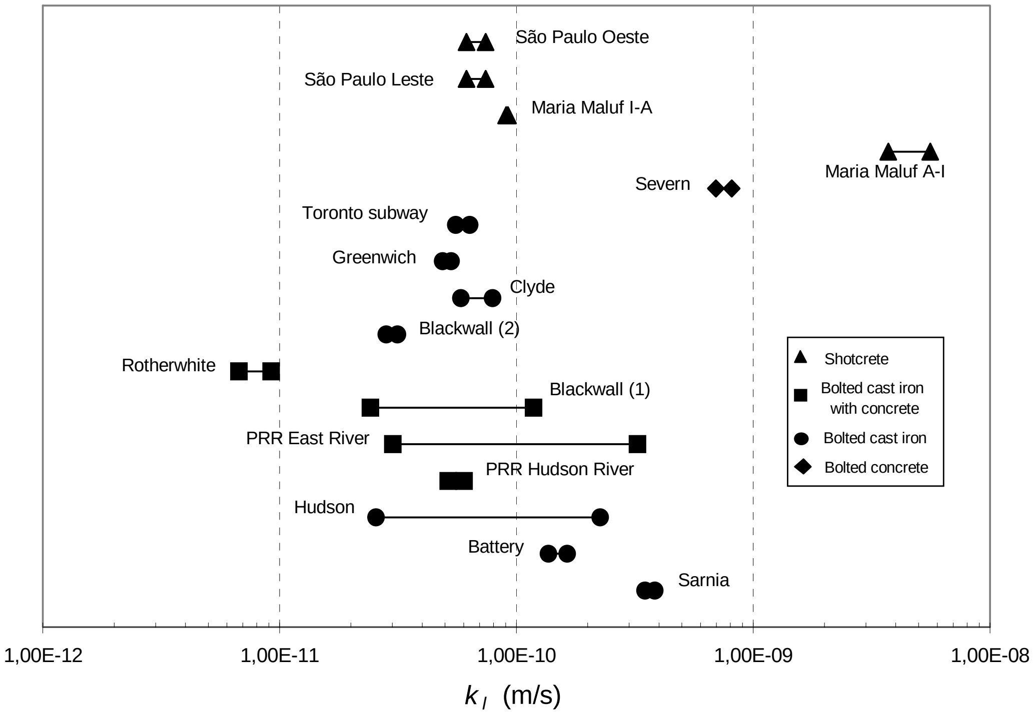

Figure 1 – Ranges of back-analyzed values of lining permeability k_l (Celestino et al., 2001)

Figure 2 shows a picture of the São Paulo Oeste tunnel of Line 1 Blue of the São Paulo Subway, with data presented in Table 1. The tunnel was constructed in the mid 80s and this section is in very good operational conditions 20 m below the water table. The tunnel was excavated in competent tertiary clay with sand lenses, and lattice girders were not used, which is one of the main factors to obtain low permeability shotcrete. In another section of the tunnel 30 m below the water table with a continuous thick layer of water bearing sand, the conditions are not as good and the infiltration rate is in the range of 4 l/m^2.day.

Figure 2 – São Paulo Oeste Tunnel Presented in Table 1

The conflict of opinions between the German and Norwegian authors exposed in the 1988 Congress reflects not only differences in the states of the practice with respect to specifications and the production of shotcrete, but also discrepancies with respect to design principles and level of reliability adopted in different countries. It should be kept in mind, on the other hand, that the levels of reliability have direct consequences on both construction and maintenance costs. According to Blindheim et al. (2005), Norwegian sub sea tunnels are constructed at rather low cost, US$ 6,000 – 10,000 (2 or 3 lanes). Very little cast concrete is used for lining, only at locations with difficult geological conditions. Most of the final lining is drained shotcrete (umbrella system), and the allowed water ingress is 14 l/m².day. This limit is attained by grouting the rock mass ahead of the excavation face. Pumping out this amount of salty water is economic in view of the low construction cost. The yearly maintenance cost is in the range of 1% - 1.5% of the initial investment. Relative costs of solutions for tunnels with drainage or impermeabilization have been presented by Insam et. al. (2005). Closed form solutions for lining loads with both solution were derived by Bilfinger (2005).

Gustafson and Stile (2005) present a rational procedure for the evaluation of stop criteria for grouting, as well as the dimensions of flow channels penetrated by the grout based on flow and pressure results.

At the other extreme of reliability requirements, water tight elements composed of sheet, and more recently, spray-on or membranes have been used, and will be discussed in depth in this Symposium. Lemke et.al. (2005) presented an overview of waterproofing methods, and indicated important details to be implemented with the use of both shotcrete or sheet membranes as waterproofing elements. Failure to consider such details has led to unexpected leakages in tunnels.

Spray-on membranes have not been applied to a significant number of tunnels yet. On the other hand, sheet membranes and the protection geotextile interrupt the structural monolithism between primary support and final lining, implying in higher volumes for excavation and secondary concrete. The geotextile equalizes the piezometric level behind the sheet membrane, because of no head loss in the contact.

4. CONCLUSIONS

Waterproofing is one of the main factors related to both operation reliability and durability of tunnels. Adequate shotcrete is one of the most important elements to achieve adequate levels of both attributes; however its use as final lining should not be generalized for any condition related to depth below water table and chemical aggressivity of the ground water. Its use for final lining is not yet accepted all over the world, even though its cost effectiveness has increased its use. Spray-on and sheet membranes are used in cases requiring a higher level of reliability. Neither of them however has reached a problem-free staus.

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