The Sealing Of Deep-Seated Swiss Alpine Railway Tunnels New Evaluation Procedure For Waterproofing Systems

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Summary: A comprehensive evaluation procedure for the sealing and drainage of the two long tunnels through the Swiss alps is performed based on an order by AlpTransit Gotthard AG and BLS AlpTransit AG. Special influences such as high geothermal heat, high pressure of mountain mass, construction, and high expectations for the service life-time – 100 years – had to be considered. Compared with near-surface tunnels, the thermoplastic polymeric materials typically used at present are more highly stressed. Polymeric products combined to waterproofing systems (waterproofing membranes: PE, PE-Cop, PVC-P, drainage materials: PE, PP, PA, PES) were submitted by the applicants and tested in a 24 months program for their ageing resistance. Existing test methods were complemented by new procedures, e.g., by resistance at elevated temperatures and in oxygen-enriched water at elevated temperatures, respectively, compression creep tests between rough surfaces, behaviour under combined lateral compression and horizontal shear, and installation tests including construction of the concrete support shell. The most important results of the four test modules with preliminary conclusions will be detailed. The installation tests showed that the waterproofing membranes develop regular folds with small radii of curvature during construction and thus locally lead to high strains in the membranes. Since most products did not meet certain requirements, optimised systems are now re-evaluated in a shortened procedure.

Keywords. Tunnel construction, polymeric waterproofing systems, evaluation, long-term behavior, ageing resistance

1 INTRODUCTION - DESCRIPTION OF PROBLEM

The two new railway connections from North to South in Switzerland, the Gotthard and Lötschberg base tunnels, are being built with one track each per gallery as double-shell tunnels. Because of the large mountain cover, the waterproofing system (WPS) between the relatively rough shotcrete outer shell and the concrete inner shell should continuously drain the attracted mountain water, protect the concrete construction against water, and locally transfer high compressive loads onto the concrete support structure. At the base, the large mountain cover of up to 2'500 m also results in rock temperatures of the order of 45°C due to geothermal effects. These conditions thus apply to the intruding water that is mostly alkaline, but may be acidic in some areas. The expected service life-time is 100 years, with no major repairs being necessary within 50 years. All waterproofing and draining materials known today have not been designed for nor ever been tested under such extreme conditions. The known standards do not contain criteria or requirements for such loads. Results of long-term tests were not available at the time and practical experience existed only for relatively short periods.
2 EVALUATION PROCEDURE

In order to effectively take into account the special conditions (mountain, choice of construction, and other boundary conditions imposed by the builders), a special task force together with the assigners developed, invited for tender, and realised a multi-part procedure for the evaluation of the waterproofing system consisting of waterproofing membrane and drainage material (E. Basler+Partner 1998). This procedure comprised:

- Ageing behaviour of the different waterproofing and drainage materials
- Behaviour of the WPS under compression creep load
- Compression/shear behaviour of the WPS
- Suitability for installation
- Synthesis

2.1 Ageing of the individual components

In this part of the evaluation, the components of the WPS are exposed for 24 months without mechanical loading to the following media: water circulated at temperatures of 23°, 45°, and 70° C, alcaline and acidic water at 50° C, oxygen-enriched water at 70° C and 3 bar pressure (test equipment shown in Figs 3 and 4), and, by burying the specimens, in an environment with aerobic and anaerobic microorganisms. At 5 points during the storage, the waterproofing membranes are tested for mass changes, longitudinal and transverse change of dimensions, mechanical puncture strength (dart impact on WPS placed on rigid support), and the drainage materials for mass changes, transmissivity within the plane, and punching resistance against a drop cone. An additional series of tests such as, e.g., tensile, thermomechanical and thermoanalytical after 3, 6, 12 and 24 months is used to determine the respective properties for a sufficiently complete description of the ageing processes.

2.2 Behaviour of the WPS under Compression Creep Load

In a separate compression test during 24 months, the WPS are stored at 0.4 MPa in alcaline water at 50° C between a planar and a strongly corrugated ripple plate (Fig. 5). The surface roughness Rt determined using the sand-filling procedure is 4.5 mm. This ripple structure consists of 169 truncated pyramids with a square base area of 256 mm², a height of 7 mm and a top area of 4 mm². Figure 6 shows the experimental arrangement for the WPS. The decrease of the thickness of the waterproofing system, the impermeability,
2.3 Compression/Shear Behaviour of the WPS

Four separate test modules are used to evaluate the short- and long-term behaviour of the WPS under the combined effects of compression (up to 2 MPa) and shear at 45°C for a 1.5 m² size specimen between the rough shotcrete surface (average surface roughness Rt 3.1 mm) and the concrete compressive support surface. The waterproofing function, the drainage capacity, and the deformation behaviour of the systems set-up are evaluated. Because of the novelty and complexity of this test it was necessary to specially design, test, and validate a suitable test set-up. The reproducibility of the test results was assured by casting one template each of an original shotcrete and concrete surface. A pipeline system inserted into the pressure plates allows heating the contact surfaces to up to 70°C. With an additional pipeline system, drainage water can be circulated into a water distribution groove placed at the center of the top plate from where it will flow horizontally through the WPS (Fig. 7). Drinking water, filtered at the inlet to remove eventual suspended particles (> 10 µm) was used. The water flowing out along the sides is collected and pumped back into the circuit. The drainage capability is measured by determining the pressure necessary for a constant water throughput of 10 l/min.
2.4 Suitability of Installation

In an experimental gallery with a 8 m high shotcrete arch of the vault, each waterproofing system (WPS) is used to seal a shotcrete surface area of 70 m² with a defined surface roughness under real conditions (humid-wet at elevated temperatures of the shotcrete surface) including construction of the concrete support shell. The type of fixation, the number of fixations, the joint type and the properties of the seams are checked as indicators for the WPS. After completion of the construction, the water flow and drainage capability, respectively, are measured by injecting a defined amount of water through a piping system into the spherical cap behind the waterproofing membrane. Later, the concrete support shell is removed and the exposed WPS is inspected for damage/bruises and impermeability, respectively, for fold-free installation and other irregularities.

3 MATERIALS TESTED

The applicants, i.e., consortia of manufacturers, suppliers, and installation companies, submitted 14 different combinations of WPS (Table 1) for the two year evaluation period. Those combinations were considered optimal for use in the alpine tunnels. The considerable differences between the submitted WPS resulted from different weight attributed to the various conditions (waterproofing, drainage function, pressure transfer, and fire resistance during installation) that had to be fulfilled simultaneously. These requirements were interpreted quite differently by the applicants.

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<th>Table 1: Types of Materials submitted for the two year evaluation procedure</th>
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Prior to acceptance in the evaluation, the applicants had to prove conformity with existing standards/guidelines, such as Sia V280 for ground-water sealing (Sia 1996) and Handbook of Geotextiles (SVG). Since these standards apply only to materials after manufacturing, some requirements were specifically increased, in particular mechanical puncture strength for the waterproofing membranes, and transmissivity and fire classification for the drainage materials.

4 RESULTS

4.1 Ageing Behaviour

After 6 months, the results were relatively heterogeneous, but after 12 months, differences in quality between the types of materials used for the waterproofing membranes and the drainage became apparent. Between 12 and 24 months, these trends were reinforced. In general, the waterproofing membranes proved to be more resistant than the drainage materials even...
though some products made from polyolefin-copolymers (PO-C) decomposed during the exposure to hot, oxygen-enriched water. Waterproofing membranes made from plasticized PVC, as expected, reacted by loss of plasticiser most strongly to alkaline water and by increasing loss of plasticiser under exposure to aerobic microorganisms. Some materials made of PO-Copolymers reacted when exposed to alkaline water. The evaluated drainage materials generally reacted more sensitively to both acidic and alkaline exposure. Some products made from polyamide (PA) and saturated polyesters (PES) decomposed in acidic water at 50°C. In hot water at 70°C, these materials embrittled even after 6 months, at 45°C between 12 and 24 months. Dimpled sheets yielded relatively minor changes.

4.2 Behaviour under Compression Creep Load

Under this type of loading, the drainage materials yielded considerable deformations and the ripple plate intruded deeply through the draining layer into the waterproofing membrane. From the compression-deformation curves (Diagram 1) the thickness of the total WPS at the load points is reduced to 0.8 mm. No WPS, however, was punctured under this creep load. Even an additional 20% strain after the test did not show disadvantageous behaviour at the contact points. In a few cases, the drainage stuck to the waterproofing membrane. Points of high stresses, e.g., at the edge of the nop, occasionally yielded first signs of stress induced cracks that increased in length between 12 and 24 months.

Diagram 1: Example of deformation curves from compression creep tests for typical WPS at 0.4 MPa distributed load on the ripple plate in alkaline medium at 50°C.
4.3 Compression/Shear Behaviour

The most severe criterion proved to be the drainage capability under lateral compression at elevated temperature (+45° C). This capability directly correlates with the time-dependent remaining thickness of the WPS. Several WPS did not meet the requirement of a maximum water inlet pressure of 0.25 bar at 10 l/min throughput in both the short- and long-term (7 days) tests (Diagram 2). The compression/shear results of the limited number of materials tested seem to indicate the following pattern for the behavior of the WPS. All WPS with dimpled sheets proved fairly well suited in spite of large deformations. Depending on the hardness, several net-type drainage materials intruded into the waterproofing membranes, starting at lateral compression loads of 1 MPa, thus limiting the water flow and finally interrupting it at loads above 1.5 MPa. Some WPS with net-type drainage materials of a modified shape and combined with a less compliant waterproofing membrane, on the other hand, fulfilled the criterion at the highest lateral compression load of 2 MPa in the short-term, as well as in the long-term test (7 days) at loads of 1.5 MPa. WPS with thick and dense non-woven fabrics as drainage materials showed an increase in water inlet pressure beyond the limit even at lateral compression loads of 0.5 MPa. Some waterproofing membranes were perforated after shear displacements of 10 mm under relatively low compressive loads (0.3 MPa), while displacements of 3 mm under the same load did not yield perforations. Passing the compression/shear tests may thus crucially depend on the specific combination of drainage material (structure and shape) and waterproofing membrane (hardness and thickness).
4.4 Suitability for Installation in the Experimental Gallery

Before the product tests were effected, three trial tests with typical WPS made from plasticized PVC and PO-Copolymers (dimpled sheet- and net-type drainage materials) yielded the test parameters. The systems were installed on shotcrete surfaces with a variable surface roughness between 3 to 7 mm and a waviness of 4:1, 7:1 and 15:1. With additional heating during the setting of the concrete the temperature in the waterproofing system rose to 55° C. After completion of the construction the drainage capability was determined. The concrete support shell was then removed and the waterproofing system exposed (Fig. 8). These tests yielded unexpected, interesting results. Both types of WPS showed deep folds in the waterproofing membrane, protruding into the concrete after the support shell had been removed (Figs 9, 10). The folds mostly ran along the vertical and extended for about 5 cm with radii of curvature of up to 3 mm. Practically, the folds are narrowly localised but highly strained zones that potentially can function as water drains. There, the waterproofing membrane is strained beyond its apparent yield point and oriented, respectively and is stressed both chemically and physically by the mountain water. The third trial test proved that WPS can be installed without fold formation. The waterproofing membrane was not damaged in any of the tests. The large waviness of the shotcrete surface, however, required additional expenditures during installation, in particular for fixation and joints. Based on the understanding gained from these tests, the requirements for the main tests could be defined and the test set-up be adapted.
5 KNOWLEDGE GAINED

It took about 12 months until equilibrium states and recognisable ageing trends were established for the different materials. After 24 months, the loads/exposures yielded clear signs of deterioration and only a few WPS and WPS-components, respectively, fulfilled all requirements. While the waterproofing membranes, on one hand, failed under some specific load conditions, the drainage materials with their formulation, on the other hand, proved to be rather unsuited for use in hot, aqueous media. The WPS selected for submission by the applicants were mostly manufactured using formulations developed for standard construction applications instead of being designed for the special requirements of the tunnel constructions. The standards usually do not require test durations beyond about 8 months, usually even shorter, and leave the definition of requirements to those responsible for the construction.

Development of folds in the plane of the waterproofing membrane produces potential failure lines and have thus to be avoided in long-term service. This requirement represents a major challenge for the usual installation procedures. The causes for folding have to be thoroughly investigated. Waviness of the backplane, the number of fixation points, the joining procedure, friction between waterproofing membrane and drainage material, the form-boards of the inner concrete shell and the temperature raise caused by the setting of the concrete are among the factors that cause surplus membrane material to protrude into the concrete at the time of construction. Preliminary experiments have shown possible ways of avoiding fold formation.

The evaluation procedure has proven to be both practical and selective. Compared with established standard test criteria, the requirements have been increased and the evaluation takes considerably longer. In order to design for ageing resistance during the intended service life, test durations of up to five years would be necessary under current test conditions. With the introduction of the evaluation procedure, the behaviour of both, waterproofing membrane and drainage material, acting together as a system, has been investigated under very high load and long-term exposure for the first time.

6 PRESENT STATE OF THE EVALUATION

By continuously informing about intermediate results and based on reports summarizing the first 6 and 12 months, the builders could continually assess the situation and adapt it to the construction program. Based on the results of the first test series a shortened evaluation procedure of 12 months duration was re-started. This program evaluated so-called “improved” waterproofing systems – systems modified within certain limits – in the same way and was recently completed. Before the final decision was taken whether a WPS passed the requirements, the results from the second test series were correlated with those from the first, since the 12 months test duration is too short to allow a definitive assessment.

The improvements essentially comprised an increased compression stiffness of both waterproofing membrane and drainage material and modified formulations for increased resistance. Certain criteria still proved to be problematic, in particular the exposure of drainage materials to oxygen-enriched and to alcaline water. The test program on improved WPS up to present yielded 8 systems that passed all requirements. These combine polyolefine- or PVC-P-based waterproofing membranes with either dimpled sheets or composite drainage materials.
The evaluation procedure is still open for new waterproofing systems. Due to the stringent requirements, other applications in civil engineering and tunnel construction with long service life-times should also be covered. Nevertheless, the effects on the waterproofing system have to be carefully analysed, assessed, and investigated accordingly.

7 ACKNOWLEDGMENTS

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