Detachment of Shotcrete Linings due to Long Term Interaction with Ground Water

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ABSTRACT

Shotcrete in long term contact with ground water is often affected by leaching and simultaneously by the formation of sulfate minerals, predominantly thaumasite. As a consequence thaumasite may be a very common finding in a large number of underground constructions. Thereby it is important to note that physical parameters like permeability or inhomogeneities are at least as important as chemical parameters like the composition of the paste, pH-values and composition of the interacting water.

The adhesion of shotcrete linings is affected by small amounts of interactions on the interface. Severe conditions may therefore be related to ground water not considered as aggressive by current standards.

Keywords
Shotcrete, tunnel, sulfate, degradation, thaumasite

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1. INTRODUCTION

Cement based materials are generally characterized by durability qualities. Durability criteria hereby are defined for laboratory tests and bulk properties of material samples. In contrast to these circumstances situations in reality look quite different and are complicated by a number of factors.

First, the severity of concrete deterioration is related to the risk of failure on one hand and to the costs of repair on the other, but service life of buildings is not related to the average quality of the building materials used.

Second, the action of the environment is composed of many different physical and chemical components which generally vary in their intensities over time and within short distance.

Third, the factor time is of crucial importance. Laboratory tests as a matter of fact have to accelerate the deterioration processes, physical and chemical test conditions are intensified accordingly. The resulting mechanism may therefore be different from the mechanisms during long time interaction.

In Switzerland shotcrete was used as tunnel lining for decades: on the one hand to protect the rock surface from disintegration, on the other hand for the repair of old tunnel masonry. Shotcrete was
often placed together with drainage elements to prevent water to drop from the tunnel ceiling as well as the formation of ice in the tunnel opening. Shotcrete was applied with and without reinforcement or by using steel fibers.

Shotcrete linings in tunnels are often in contact to percolating ground water. Typically the linings are saturated with water only in few areas and water is penetrating the shotcrete locally. Already small and often hidden amounts of concrete alteration at the interface to its support lead to significant reduction of adhesion and corresponding risk of detachment.

2. INTERACTION OF GROUND WATER WITH SHOTCRETE LININGS

Elevated water saturation of shotcrete is often associated with pathways (joints, cracks) through the tunnel lining. The formation of layers of secondary minerals on the surface of a shotcrete lining could only be observed with relatively thin shotcrete and sodium sulfate hydrates (Figure 1). Surface scaling of concrete due to the crystallization of salt near the surface is rare in tunnels (maybe due to high levels of humidity). In most cases water is moving along local and permeable inhomogeneities through the shotcrete lining. Low flows of water are accompanied by formation of calcite and/or water soluble salts on the surface of the lining close to the intersection. Larger flows of water are frequently escorted by biofilms on the shotcrete surface (Figure 2) and water soluble salts may form in the lateral drying region of the wet concrete. Under biofilms the concrete surface may show phenomena of cement paste dissolution and erosion due to acid attack.

![Figure 1. Shotcrete lining in the service tunnel “St. Gotthard” (upper part of the wall) showing a more or less uniform cover with bright efflorescence. Dark (wet) regions within the shotcrete mark localities with water transport and evaporation through the shotcrete [1].](image1)

![Figure 2. “Gotschna” tunnel: ground water locally penetrating the shotcrete lining. Depending on the amount of running water large amounts of biomass may form. The white mass in the center of the picture represents a colony of sulfur bacteria.](image2)

In contrast to these surface phenomena the back side of underground constructions is much less accessible for investigation but more prone to chemical interaction. Figure 3 is indicating schematically locations within the cross section where concrete degradation due to interaction with ground water takes place.
Several tunnel constructions were examined because of problems with detaching shotcrete linings (Two examples given in Figures 4 and 5). Samples of the shotcrete were investigated for alteration in their microstructure and mineralogical composition respectively to elaborate the cause of loss of adhesion. Water samples were analyzed in the laboratory as well.

Shotcrete is mostly characterized by a diffuse layering due to the spraying procedure (Figure 7). Alteration and interaction with percolating water produces complicated deterioration-textures and chemical zonations along the contact to the shotcrete support and to a lesser extent along the layer contacts within the concrete (schematically shown in Figure 3). On a microscopic profile starting in the unchanged shotcrete towards the above mentioned contacts the alteration increases and 3 distinct zones can be distinguished (schematically shown in Figure 8): the zone of leached cement paste followed by the lack of portlandite and the general grain size reduction of cementitious phases give evidence for general dissolution processes. The corrosion zone is characterized by complete dissolution of cement paste and more or less intensive formation of secondary phases resulting in a highly porous and mechanically weak material (Figure 6). The transitions between the regions of different state of alteration are quite sharp. A detailed description of the microscopic and chemical aspects of zonations in deteriorated shotcrete (tunnel lining) is given in [3].
In intensely deteriorated samples the growth of secondary minerals in small veins is superimposed onto the chemical dissolution phenomena [4]. Cracks, veins and pore spaces are filled with very fine and fibrous matter. In relation to the interaction of ground water in tunnel concrete the formation of sulfate containing minerals was dominated by thaumasite. Ettringite on the other hand could be detected as recrystallized needles in air voids surrounded by unaltered paste which is interpreted as a ordinary consequence of high degrees of water saturation over longer periods of time [5]. Thaumasite in contrast is associated with different kind of chemically altered or deteriorated concrete [6].

The composition of water samples from the tunnels of “Bauen” and “Koblenz” indicate contents of sulfate ($\text{SO}_4^{\text{2-}}$) in the range of 50 to 300 mg/l, bicarbonate ($\text{HCO}_3^{-}$) 50 to 200 mg/l and low amounts of magnesium: 5 to 15 mg/l. The water samples are dominated by sodium, chloride and calcium.

3. DISCUSSION

The stability of hydration products in hardened cement paste is depending on the chemical composition of the pore solution which itself is chemically buffered by the latter [7, 8]. As a consequence the interaction with an aqueous environment of different composition is not resulting in a continuous alteration over distance but in the formation of a zonation pattern: regions with different solid compositions show relatively sharp transitions between them. This gives evidence of a moving boundary behavior in the opposite direction of the diffusion flux [9].

At a fixed point of consideration different corrosive processes follow each other because the reactive front is moving with time. These processes include dissolution of cementitious phases, transportation of dissolved chemical species and (re-)precipitation of secondary minerals. The water flow through a crack is always leading to leaching of the crack walls (Figure 8). Based on the observations in field samples the formation of thaumasite in shotcrete lining is strongly related to a preceding or simultaneous leaching process. The sulfate content in ground water samples from situations showing thaumasite formation in shotcrete was low and hardly aggressive corresponding to current standards.
The observed textural relationships indicate that chemical attack is triggered by permeable inhomogeneities which serve as pathways for the percolating water. Similar results for shotcrete linings are published by Haglia et al. [10] The zonations of leaching and thaumasite formation is comparable to the findings of Sibbick et al. [11], whereas in our samples the coexistence of thaumasite and portlandite was rarely detected.

Figure 8. Schematic presentation of a shotcrete lining with local pathways along internal layers and along the interface leading to the evolution and the propagation of defined zones of alteration.

Extensive leaching of concrete in underground constructions is not only important for the degradation of the building material itself, it may also cause the formation of precipitates (calcite) in the drainage system. This process leads to the failure of the drainage and to a pressure increase which itself will force the water to penetrate new pathways.

4. CONCLUSIONS

The observed textural relationships of deteriorated shotcrete linings in underground constructions indicate that chemical attack is triggered by permeable inhomogeneities which serve as pathways for the percolating water.

In all investigated tunnel structures with shotcrete in long term contact with ground water the processes of leaching and the formation of sulfate minerals, predominantly thaumasite, have been detected along internal pathways and along the interface of the lining. As a consequence thaumasite may be a very common finding in a large number of underground constructions. The concentration of sulfate in the ground water and due to the formation of thaumasite instead of ettringite the use of cement with low contents of aluminum seem to be less important.

The adhesion of shotcrete linings is affected by small amounts of interactions on the interface. In this regard not only water regarded as ”aggressive” corresponding to regulations has to be considered but a wide range of chemical compositions, severe conditions may therefore be related to ground water not considered as aggressive corresponding to current standards.
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REFERENCES