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Measures for the reduction of sinter formations in tunnels

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Abstract. A considerable part of the maintenance costs of tunnel structures is related to the inspection, maintenance and repair of the drainage system. The drainage system of tunnels is frequently clogged with Calcium precipitates. Cleaning and water conditioning are cost-intensive for operating companies. Apart from the direct costs associated with inspection, maintenance and repair works of the drainage system indirect costs are generated, such as by the blocking of the tunnel while inspection, maintenance or repair or by the reduction of the permitted operation speed. Sintering and clogging of the drainage systems is mainly caused by dissolution of cement minerals in concrete and mortar and/or by inadequate design and construction of the drainage system and/or grubby workmanship. With long-term studies and in-situ experiments in Austria traffic tunnels the specific input factors for sinter mechanism have been identified and appropriate counter measures could be defined. In particular modified mix designs for shotcretes and mortars have proven to bring a significant beneficial effect. By means of constructional measures and by the application of hardness stabilizers a further reduction of hard deposits inside the drainage system is achievable. The paper will deal with the specific aspects and will propose adequate counter measures.

1. Introduction

In the recent past in Austria a large number of traffic tunnels have been constructed or are still under construction. In particular long railway tunnel projects, such as the Koralm tunnel (l = 33 km) or the Semmering Base tunnel (l = 27 km), but also long road tunnels, such as the Gleinalm tunnel (l = 8 km) required new considerations in regard to the simplification and reduction of maintenance.

The drainage system of tunnels is frequently clogged with Calcium precipitates. Assessments on railway tunnels have shown that around 15 – 20 % of the entire inspection and maintenance works are in relation to the drainage system. For road tunnels similar dimensions are well known, leading to high direct costs for inspection and maintenance of the drainage system, e.g. for motorway tunnels between 5,000 and 10,000 EUR per kilometer tube and year. Apart from the direct costs associated with inspection, maintenance and repair works of the drainage system indirect costs are generated, such as by interfering the traffic or blocking of the tunnel while inspection, maintenance or repair. These works have high negative impact on the operation, the operational costs as well as on the capacity of the tunnels. Thus, from the early stages of the design of a tunnel project special effort has also to be made to find solutions to minimize these costs and negative interferences.

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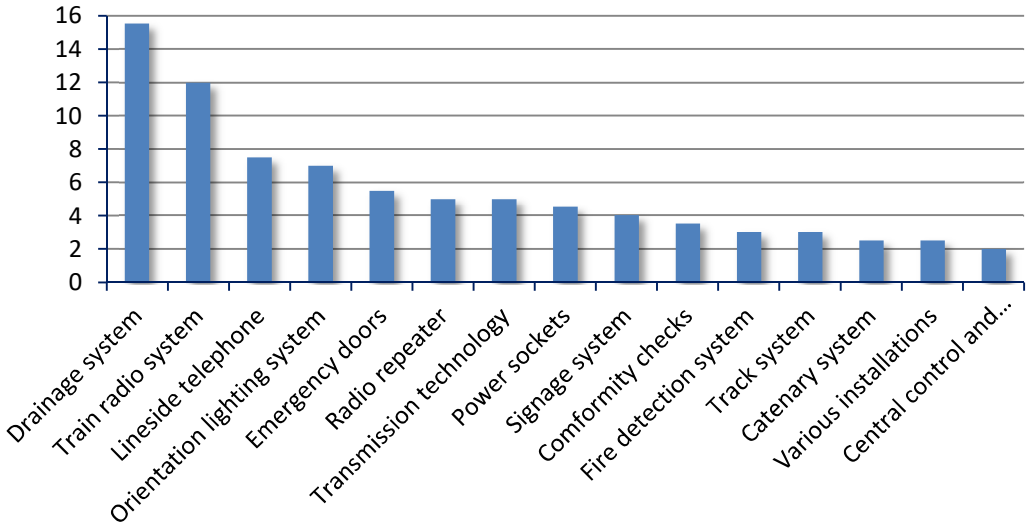


Figure 1. Average percentage of inspection, cleaning & maintenance works for various installations in Austrian railway tunnels (after [1]).

2. Sinter mechanism in tunnels

The phenomenon of iron precipitations will not be discussed in this article. In case of carbonate dissolution in tunnel drainage systems mostly Calcium carbonates precipitate from aqueous solutions, which are generated from local groundwater and the reaction with the shotcrete of the tunnel construction [2], [3]. Accordingly, the chemical composition of the drainage solutions depends on the evolution of the local groundwater as well as on the chemical composition and reactivity of the materials used for construction.

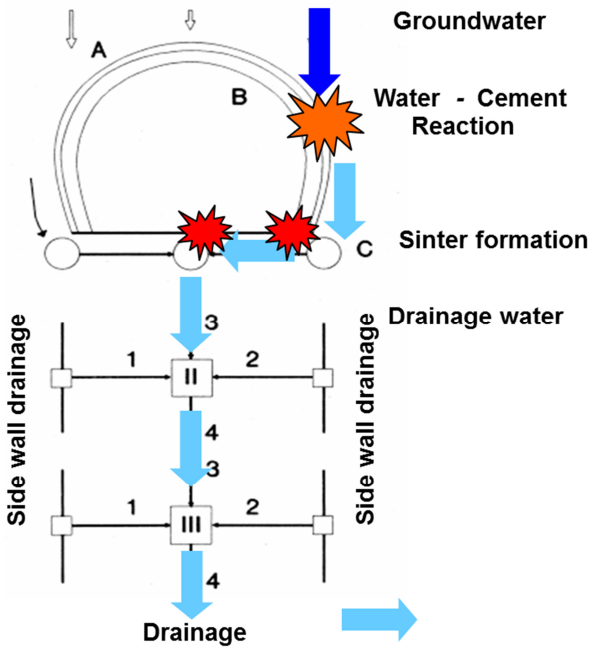


Figure 2. Simplified tunnel drainage concept and groundwater – construction interaction (after [3]).

Frequently the precipitates consist of the minerals Calcite ($CaCO_3$), Aragonite ($CaCO_3$) and also Brucite ($Mg(OH)_2$). The general mechanisms of interaction are described by [3] as follows.

2.1. Dissolution of limestone

The drainage solutions are gained from groundwater, which dissolves carbonate minerals from the natural rocks. The dissolution of carbonates is promoted by the uptake of carbon dioxide from the Earth´s atmosphere. Calcium carbonates dissolve according to the overall reaction

$$CO_{2(gas)} + H_2O + CaCO_3 = Ca^{2+} + 2HCO_3^- \quad (1)$$

The dissolution usually results in slightly alkaline Calcium bicarbonate solutions. The concentration of total dissolved carbonate strongly depends on the primary content of carbonic acid and the occurrence of solid carbonates.

2.2. Reactions at the shotcrete

As the groundwater gets into contact with the shotcrete of the tunnel, complex mineral water reactions appear. Simplified, the Portlandite of the shotcrete dissolves which results in an increase of the Calcium concentration and pH. Drainage solutions can reach pH values up to 13 and more. On the other hand, Calcium ions can be fixed by the precipitation of Calcium carbonate and sulphate minerals directly at the shotcrete. Newly formed sulphate minerals at the shotcrete may comprise Gypsum, Ettringite, Monosulfate and Thaumasite, depending on the availability of aqueous sulphate ions. In highly alkaline solutions Brucite can be precipitated.

2.3. Mechanisms of carbonate sinter formation

Calcite precipitation from the drainage solutions can be induced by the dissolution of Portlandite in the primary groundwater at the shotcrete. The dissolved Calcium and carbonate ion can be precipitated according the equation

$$Ca(OH)_2 + 2HCO_3^- + Ca^{2+} = 2CaCO_3 + 2H_2O \quad (2)$$

as supersaturation with respect to Calcite is reached. However, once the solutions come into contact with the Earth's atmosphere, the internal partial pressures of CO_2 in the solutions control the CO_2 exchange with the atmosphere and ongoing carbonate precipitation.



Figure 3. Typical sinter formations (in whitish colour) on the surface of a shotcrete lining.

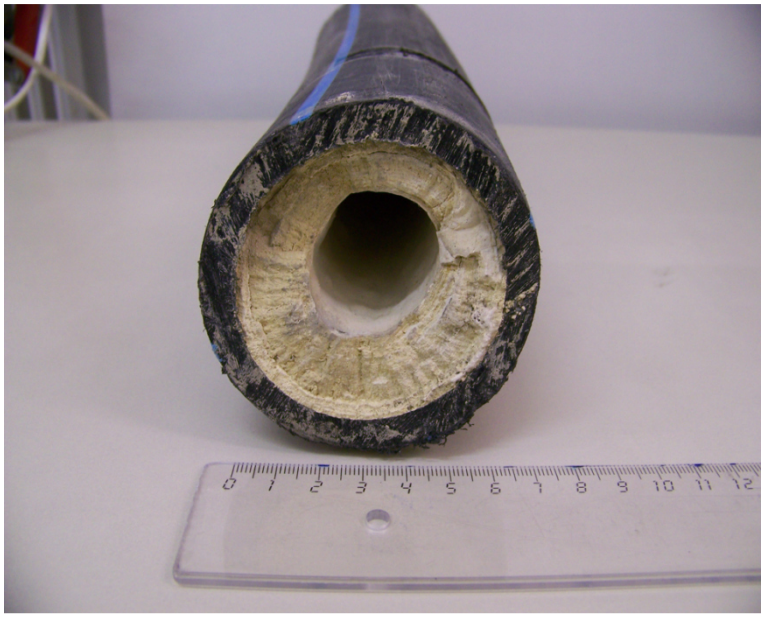


Figure 4. Sinter crusts inside a drainpipe (after [3]).

Thus, carbonate precipitation in drainage systems may cause serious problems due to the reduction of the cross section of drainage tubes (Figure 4) and the pollution of receiving streams by suspended carbonates and ongoing sinter formation.

3. Impact factors and counter measures

Consequently, the main impact factors on sintering are:

- the composition of ground water,
- the materials of tunnel structure,
- as well as constructional details.

To reduce the negative effects of sintering right from the early stages of a project special attention shall be paid towards these impact factors.

3.1. Composition of ground water

As stated above quantity, the chemical composition of ground water as well as the saturation respectively under-saturation of ground water has high influence to the dissolving behavior. Therefore it is recommended to analyze the prevailing groundwater conditions also regarding to their sinter-relevant aspects. These aspects shall be considered as early as of the first ground investigation campaigns and can be continued over all periods of design and construction.

On the example of the Koralmtunnel it has been shown that by means of specific hydrogeological monitoring, carried out also subsequently to the construction, zones with high and zones with low sinter potential could be identified [3] and specific counter measures could be defined on the basis of this knowledge.

The ground water can be treated by means of inhibitors, e.g. Polyaspartic acid or Polysuccinimid with the effect that the precipitation mainly occurs in a colloidal matter not forming hard crusts in the drainage system. On the other hand several examples have shown that the overdose of inhibitors or the application of inappropriate products may cause negative effects. This might lead to an overfertilization of waters with the result of a significant growth of aqueous slime and felt.

The application of supply stones had been tested in several projects. Also their functionality depend on specific project respectively groundwater conditions. Extensive tests in this regard have been carried out for the Gotthard Base tunnel [4] leading to the development of a tailor made hardness stabilizer system.

On the example of the Austrian Lainzer railway tunnel the application of supply stone showed no convincing results. After intensive investigations it was described [5] that under the specific conditions of this project the most effective solution was to treat the groundwater by means of the liquid dosing of diluted hydrochloric acid instead of the abovementioned organic acids. The reaction of the hydrochloric acid with partly formed sintering crusts leads to the dissolution of the calcite.

The best knowledge of the sinter relevant input parameter of the groundwater conditions, therefore, is mandatory. Specific hydrogeological monitoring programs shall therefore be mandatory parts of the project. System, application and dosing of inhibitors strongly depend on the project specific groundwater conditions and shall be provided as a tailor made solution for each project.

3.2. Custom-made concretes and mortars

Carbonate sinter formation in tunnels are, as stated above, closely related to the groundwater-concrete interaction. Sinter formation can significantly be reduced by an adequate construction and by using tailor-made construction materials. Lab experiments show that shotcrete with low contents of Portlandite and sulphate active minerals as well as with low permeabilities should be used for a sustainable reduction of carbonate sinter formation. In case of shotcretes these modifications have already been incorporated in the national guidelines [1].

Based on the study results for the Koralm tunnel appropriate recipes for shotcrete under construction site conditions are developed using low hydraulic cement content to reduce Portlandite formation during the hydration, alkali-free setting accelerators, and proper conditions to avoid fissure formation.

One suitable composition was obtained by using around 280 kg/m^3 of CEM I 52.2R, 140 kg/m^3 of AHWZ (pre-processed latent hydraulic acting material such as fly ash), and about 7 wt.% of an Aluminium sulphate containing setting accelerator. Results from water-shotcrete interaction experiments confirmed that such tailor made shotcrete can significantly lower the liberation of Ca^{2+} and OH^- ions into the solution. The Ca^{2+} liberation can be reduced by about 65% (!) by the application of the above recipe in comparison to common shotcrete compositions. Advanced shotcretes with respect to improved workability or specific fields of application are meanwhile applied (e.g. 320 kg/m^3 of CEM I 52.5R, 110 kg/m^3 of AHWZ, 40 kg/m^3 of steel fibers or 320 kg/m3 of CEM I 52.5R, 102 kg/m3 of AHWZ), showing also excellent early strength behaviors.

Already the optical impressions of the shotcrete lining constructed with such modified shotcretes shows a significantly improved visual appearance.



Figure 5. Visual appearance of shotcrete lining without sinter efflorescence inside the Koralm tunnel lot KAT1.

Segments applied in shield-TBM tunneling can be considered to be uncritical in respect to dissolution due to their dense concrete structure and their long curing time. However, also in mechanical excavations considerable amounts of backfill grout mortars are in use. These mortars (in case of a drained tunnel system), as well as mortars used for grouting and rock bolting still provide a significant sinter potential. Verbal reports from the Swiss Lötschberg tunnel or from HSR Frankfurt – Köln report of at least area by area heavy sinter deposits due to heavy grouting measures.

Measures for further reduction of the sinter potential of mortars analogous to the above mentioned shotcrete modifications have to be consequently further developed. Manufactured products already available on the market, such as TIWOFILL mortar, show satisfying developments, however, further investigations, such currently running in accordance with the Semmering Base tunnel construction indicate that there is still a remaining space for further improvements.

3.3. Constructional details

Calcite precipitation from the drainage solutions can be induced by the dissolution of Portlandite in the groundwater at the shotcrete. If a supersaturated solution comes into contact with the Earth's atmosphere, the internal partial pressures of CO_2 in the solution control the CO_2 exchange with the atmosphere and ongoing carbonate precipitation.

The mechanisms of Calcite precipitation in the drainage solutions show that the drainage system should be designed to minimize the CO_2 exchange with the atmosphere. Wide and long-lasting contact with air as well as turbulent flow of solutions has to be avoided. In addition an easy accessibility for inspection and cleaning of the drainage system shall be part of a proper design. In case of the Koralm tunnel the main drainage pipe is located directly under the centerline of the track, allowing easy rail bound inspection and cleaning [1], [3].

By using filter gravel with a reduced addition of cement (less than 200 kg/m³) additionally a reduction of nutrient supply can easily achieved.

These measures have to be accompanied by proper workmen ship, avoiding steps, kinks or blockages of the flow path. By such an approach the precipitation of Calcium carbonate can be significantly reduced.

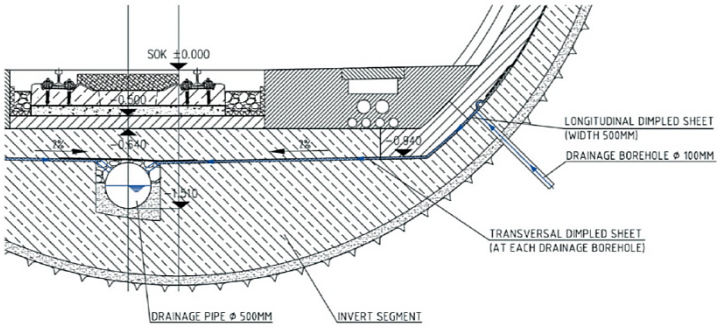


Figure 6. Invert detail of the Koralm tunnel with laminar flow path and only one central main drainage (after [3]).

In case of remaining precipitations these might be treated with scale inhibitors, e.g. hardness stabilization, considering the sensitivity of such counter measures. Once carbonate sinter is formed in the drainage system, a proper drainage design for the discharge of drainage solution and for simplified cleaning actions is essential for cost-efficient maintenance of the tunnel system. The alignment of pipelines shall be smooth, with short shaft distances, sufficiently large drainage pipes with sufficient space for sinter formation, as well as smooth-walled pipe surfaces, which do not show any damage.

4. Conclusion

The drainage systems of tunnels are frequently clogged with calcite precipitates. Cleaning and water conditioning are cost-intensive for the operating companies. Multiannual investigations and in-situ experiments in the recent past in Austria and other European countries have shown that the dissolved Calcium in the drainage solutions derives from the groundwater and especially from the dissolution of Portlandite at the shotcretes and mortars. By using custom-made shotcretes sinter formation can be significantly reduced. Matched to the specific groundwater conditions these custom-made shotcretes are meanwhile successfully applied. Analogous developments have also to be made with further construction materials, e.g. grouting mortars.

With a design of flow paths avoiding turbulent flows and less contact to Earth's atmosphere the precipitation of Calcium carbonate can be significantly reduced, too.

The consideration of these measures provide an important contribution for the significant reduction of maintenance and repair works of tunnel drainage systems, yielding to less interference in operation and a significant reduction of operational costs.

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