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Precipitations in the Tunnel Drainage System – Optimized Shotcrete Mix-Design

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Abstract

In central Europe double-shell tunnel lining is a well proven technology. The construction consists of a primary lining (e.g. shotcrete) and an inner lining (e.g. cast-in-situ concrete). For serviceability reasons and the durability of the tunnel, the structure has to be protected against water ingress. One possibility is to drain off the water depressurized (“umbrella insulation”). The water is collected at the edges of the tunnel sidewalls in drainage pipes, so that the tunnel lining is relieved from water pressure.

On its way from the surrounding ground to the drainage pipe the groundwater gets in contact with cement bound materials, might change pressure, temperature, pH-value and finally comes in contact with the atmosphere. The water composition, lime-carbonic acid equilibrium, carbonate hardness itself as well as leaching of calcium hydroxide can lead to precipitation of calcium carbonate. With such precipitations the drainage pipes can get clogged. Subsequently uncontrolled water draining can occur or the water pressure on the tunnel lining may increase and the construction can be damaged. From time to time the drainage system must therefore be maintained. To minimize the tunnel maintenance work in traffic tunnels it is therefore crucial that precipitations are reduced to a minimum.

The aim of an ongoing Bavarian research project is the improvement of shotcrete mix-design regarding reduced leaching of calcium hydroxide and hence reducing precipitation potential. The leaching behavior of new and already known binder-compositions is investigated. Commonly leaching of calcium hydroxide can be reduced by replacing part of the cement in the binder with supplementary cementitious materials (SCM). But especially in case of shotcrete the early strength development should not be influenced substantially.

This paper presents results from lab tests and sprayed mortar tests with known and new cementitious materials. Furthermore, influences on the test procedure as well as basic principles of the precipitation mechanism will be discussed. In that context a method for the simulation of calcium diffusion in cement based materials will be briefly presented.

1 Introduction - Double-shell tunnel lining and drainage systems

For the serviceability and durability of a tunnel it is important that the construction is protected against water ingress. Double shell tunnel lining is a quite common system to manage this problem (Figure 1). The shotcrete serves as primary support stabilizing the tunnel during excavation. But in many cases shotcrete does not form part of the designed permanent lining due to possible damages caused by early loading, high deformations, sequential excavation etc. [6]. For this reason, among other things, there is a need for a second permanent cast in situ concrete lining. The insulation against water ingress is generally achieved using a membrane-insulation-system consisting of a geotextile-layer and a waterproof polymer sheet membrane (mostly PVC or PE). The insulation layer is situated between the shotcrete and the concrete inner lining. The insulation layer may be realized as a full-round watertight membrane, which then might be exposed to full underground water pressure. But this system is less common in tunnels with high overburden and sensitive to defects, more commonly used is a so called “umbrella insulation” [6].

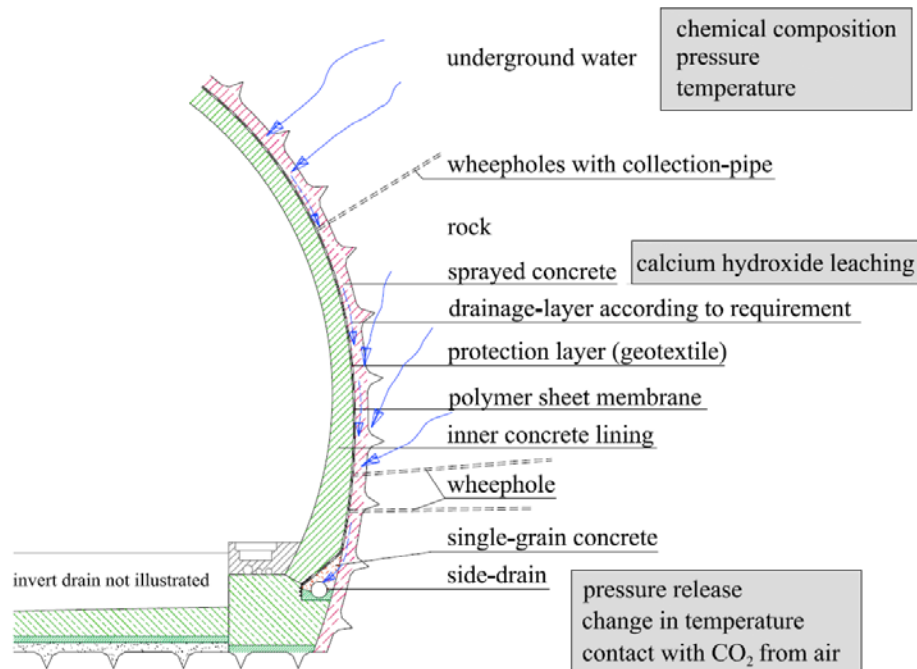


Figure 1: The way of the water from the rock to the drainage pipe [10]

Umbrella insulation means, that the underground water is drained off depressurized. Water, seeping into the tunnel, is passing the shotcrete lining or other cement bound materials, then seeping in the “gap” between shotcrete and insulation layer. The geotextile, the rough shotcrete surface and irregularities between the outer lining and the shotcrete give way for the water transport. This water is collected at the edges of the tunnel sidewalls in drainage pipes (Figure 2), so that the tunnel lining is relieved from water pressure. The pipes lead the drained water to the tunnel portal or a tunnel collector located in the center of the tunnel [10].

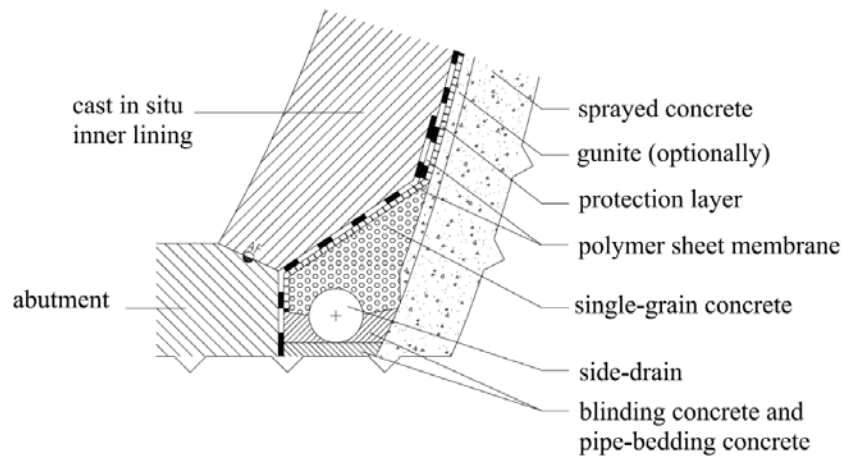


Figure 2: Common detail of the drainage pipe situated at the lower end of the tunnel side wall (bench) [10]

The inner lining in combination with sheet insulations ensures long time serviceability and enhanced durability. But the system of double shell tunnel lining has not only advantages. In case of umbrella insulation, there can be certain problems with the secondary drainage system, especially the drainage pipes. Precipitations in the drainage pipes are a common seen phenomenon (Figure 3). With time, the drainage pipes can get clogged and the water cannot flow off.



Figure 3: PP drainage pipe with precipitations. Picture: M. Testor, BEG

Subsequently the water pressure increases and the construction can be damaged. The drainage pipes need to be cleaned in regular intervals to assure the functionality of the drainage system. In order to minimize tunnel maintenance costs and traffic obstructions in tunnels, it is therefore crucial that efforts are made to reduce precipitations to a minimum.

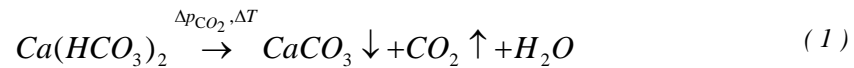
2 Precipitations

2.1 Precipitation mechanisms

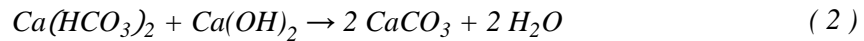
The main influencing parameters leading to precipitations in the drainage system of tunnels concern the interaction of the chemical composition of the underground water with cementitious materials.

On its way from the surrounding ground to the drainage pipe the groundwater gets in contact with cement bound materials, might change pressure and temperature and finally gets in contact with the atmosphere (Figure 1). The contact with the cementitious materials leads to an increase of the pH-value due to the dissolution of alkalis and calcium hydroxide. On the other hand the lime-carbonic acid equilibrium of the water might get strongly influenced from this, leading to precipitations.

The lime-carbonic acid equilibrium basically describes the amount of dissolved calcium hydrogen carbonate ($\text{Ca}(\text{HCO}_3)_2$) under the actual environmental conditions (pressure, partial pressure of CO_2 , temperature). The amount of dissolved calcium hydrogen carbonate (actually of earth alkalis) is called carbonate hardness of the water. For water with moderate to high carbonate hardness the change of pressure, temperature and especially the change of partial pressure of CO_2 cause precipitation of calcium carbonate according to reaction (1).



For the same water, i.e. moderate to high carbonate hardness, also the change of the pH-value caused by the dissolution of alkalis and calcium hydroxide from the hydrated cement leads to precipitation of calcium carbonate as described in reaction (2).



Another mechanism leading to the precipitation of calcium carbonate is the leaching of calcium hydroxide, resulting from cement hydration. Due to the uptake of CO_2 from the surrounding atmosphere the dissolved calcium hydroxide precipitates as calcium carbonate. For further details it is referred to [10; 4; 17; 16].

As can be seen calcium hydroxide plays an important role in precipitation mechanisms. Therefore the binder should be modified in order to minimize leaching of calcium hydroxide. This can be performed by lowering the clinker content of the binder and adding supplementary cementitious materials like slag or fly ash. By this the amount of leachable calcium hydroxide can be reduced [14].

2.2 Simulation of calcium leaching and calcium diffusion in cement based materials

In the following section a material model for calcium dissolution/diffusion is briefly presented to understand the main parameters for the dissolution behavior of calcium from concrete. This model was developed within a research project at the University of Innsbruck in cooperation with Geosystems (FFG (= Austrian Research Promotion Agency Ltd.) project "Tunnelzement", project number 824908). The underlying material function helps to calculate the Ca-Release of concrete or shotcrete taking into account different mix design and the mineralogy of the clinker and the binder. Further details are given in [1; 12; 13].

Possible sources for the leaching of calcium ions in concrete may be the cement matrix, the pore solution or calcareous aggregates. Our lab tests have clearly shown that the leaching behavior of concrete is primarily determined by the pore solution and the cement matrix. The cement matrix shows in contrast to the crystalline limestone aggregates a significantly higher Ca-solubility, so that an additional contribution from the aggregates is neglected in the following. The calcium equilibrium concentration of the pore solution can be estimated approximately as a solution saturated in calcium hydroxide with $c^{eq}=0.022$ mmol/l.

Calcium leaching occurs when the calcium concentration of the pore solution is lower than the chemical equilibrium concentration. Normally we can assume that the ground water has a significantly lower calcium content than the pore solution of the concrete. The resulting concentration gradient leads to a migration of the calcium ions from the pore fluid to the groundwater and to an accumulation in the groundwater driven by diffusion. If the water is constantly renewed by the groundwater flow, an equilibrium is constantly prohibited and a more or less continuous abstraction of calcium ions from the pore water solution takes place. The reduction of the content of calcium ions in the pore water results in a leaching of calcium from the hydration products of the cement matrix.

The dissolution of calcium is described (e.g. in [18; 3; 5; 7; 8]) as an instantaneous dissolution of calcium bound in the solid skeleton and Fick-type diffusion of calcium ions from the matrix in the pore solution. Thus, the calcium concentration in the solid skeleton s can be expressed as a function of calcium concentration in the pore solution c assuming a local thermodynamic equilibrium if the Si-concentration in the matrix remains constant. With decreasing calcium concentration c in the pore solution of cement the different main hydration products are dissolved/decalcified subsequently:

- portlandite
- Al-,Fe-hydration phases and sulfates (ettringite, monosulfate)
- CSH-phases

Figure 4 shows the nexus between the calcium concentration bound in the solid skeleton s (mol/dm) and the calcium concentration in the pore solution expressed as a dimensionless ratio c/c^{eq} . The graph describes a material function of the reference mortar calculated by the simulation model.

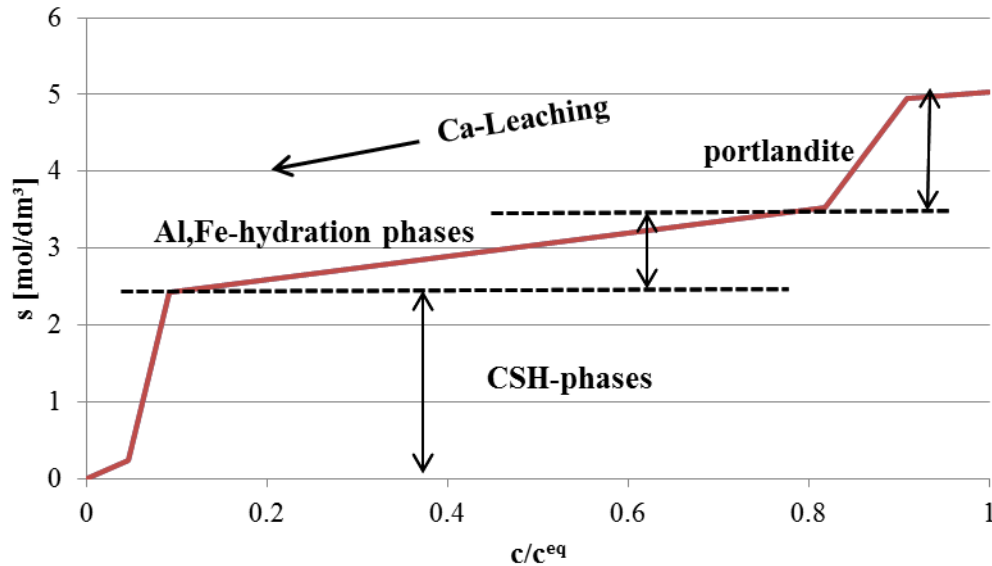


Figure 4: Material function of calcium leaching from the cement matrix

Firstly portlandite is dissolved from the solid skeleton, in the case $0.81 < c/c^{eq} < 1$. The calcium concentration s decreases depending on the calcium concentration from calcium hydroxide bound in the solid skeleton s_{CH}^0 . The other main cement phases are following subsequently with decreasing c/c^{eq} .

In the pore fluid the calcium transport occurs along the concentration gradient due to diffusion processes in accordance with the Fick's law. This requires the assumption of a more or less coherent system of capillary and macro pores in the concrete. The transport properties are mainly determined by the porosity. The increasing leaching of calcium ions from the solid skeleton is expected to enlarge somewhat the porous space volume, and hereby increase diffusion. The apparent calcium concentration in the solid skeleton/cement matrix corresponds not only with the calcium concentration in the pore solution but also with the increase of the pore space. The calcium concentration in the pore solution c can be correlated to the pore space volume Φ using a material function based on the results of nanoindentations tests of intact and completely decalcified cement samples as presented in [2].

The basis for the calculation procedure is the mineralogical data of the cement matrix and the concrete mix design. The mix design gives values for volumes fractions of the aggregates, water, hydraulic binders and air voids (macropores) per cubic meter of concrete.

Based on this data the volume fractions of the hydration products in the solid material phases as well as the capillary pore space (pore widths < 20 nm) can be calculated with the hydration stoichiometric model associated to Tennis & Jennings [15].

In combination with the transport/leaching mechanism, a specific material function connects the pore space development to the calcium concentration in the pore fluid c . Figure 5 shows the material function for pore space-change depending on the calcium concentration in the pore fluid (given as the dimensionless ratio c/c^{eq}), calculated with the simulation model for the reference mortar.

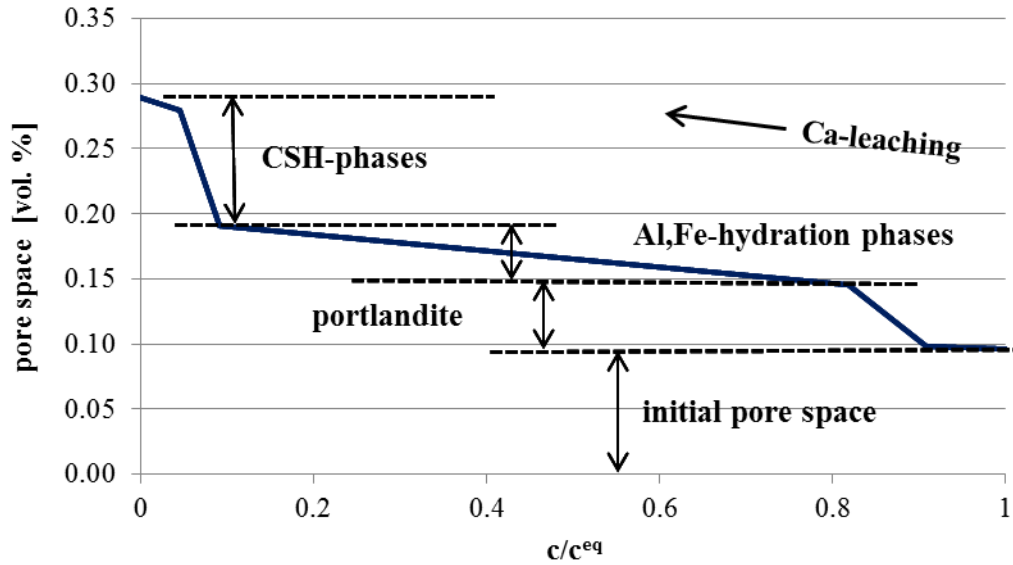


Figure 5: Material function for the connection of pore space volume and calcium concentration in the pore solution c using the example of the reference mortar

The initial pore space consists of the capillary pores calculated with the hydration model and the macropores of the concrete given by the volume fractions of the mix design. The decrease of calcium concentration in the pore fluid leads to an increase of additional pore space. Firstly calcium hydroxide is dissolved followed by dissolution/decalcification of calcium from the other phases subsequently as described above.

According to these considerations/assumptions a numerical calculation method/software tool has been developed based on the field equation for a combined leaching/transportation mechanism presented below:

$$\frac{\partial}{\partial t}(\phi c) + \frac{\partial}{\partial t} s = \frac{\partial}{\partial x} \left(D_{eff} \frac{\partial}{\partial x} c \right)$$

with:

- ϕ = pore space volume
- c = calcium concentration in the pore fluid
- s = calcium concentration in the solid skeleton
- D_{eff} = effective diffusion coefficient

The derivation of the numerical calculation model, the validation and the solution by discretization based on finite element method is described in detail by Pichler et al. [12] and Bernstein et al. [1].

The model can be used for the simulation of calcium dissolution/diffusion and the results can be presented graphically. An example of the obtained values of the Ca-solution from the reference

mortar is shown in Figure 6. The graphs of the calcium leaching of the three main hydration phase groups (portlandite, Al-, Fe- phases and CSH phases) show the sum values respectively.

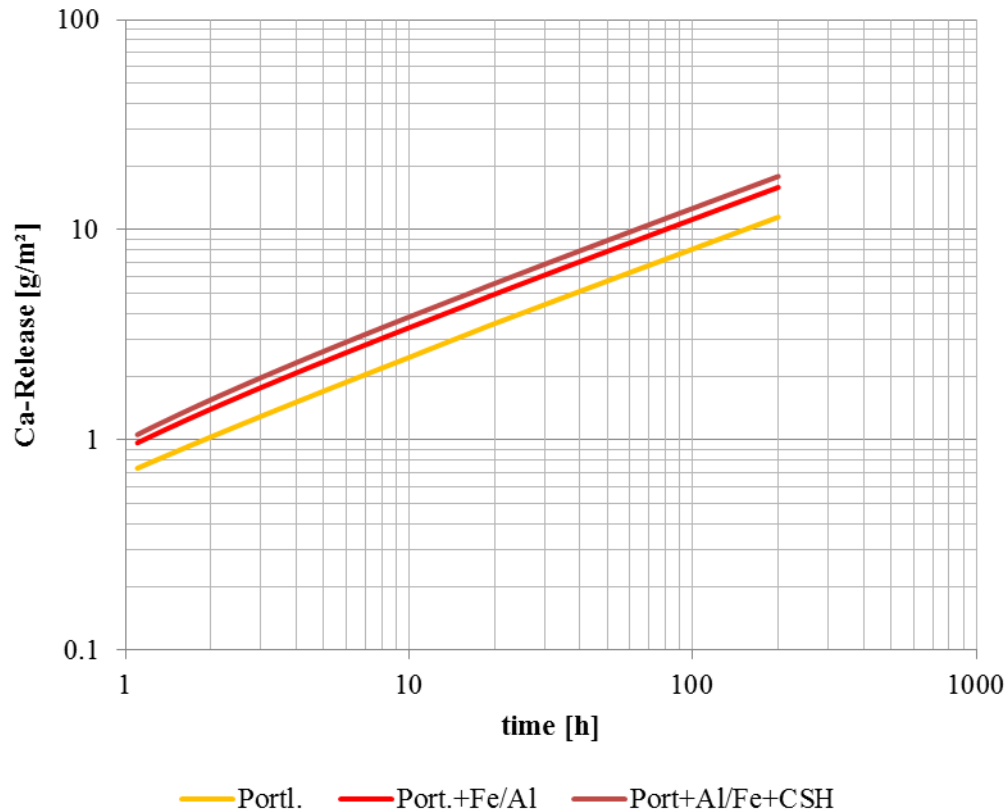


Figure 6: Simulation of Ca-Release from the reference mortar proportional from the different main mineral phases

Besides the Ordinary Portland Cement, shotcrete often contains granulated blast furnace slag and fly ash as part of the binder. The hydration model and the methods to determine the initial concrete composition was therefore extended to include those two supplementary cementitious materials (SCM).

The model offers the possibility for a better understanding or evaluation of the experimental results, which often have only a singular character. Parameter studies for the evaluation of relevant control parameters and their effects can be easily carried out with the model. At present, the theoretical calculations are going on to be compared with the results of leaching tests, which are carried out within the recent research project (see the following chapter). The results can be used to optimize shotcrete mix design as well as the test procedure of leaching tests.

One of these possibilities is shown in Figure 7. The results of long term measurement of leaching tests with different mix-design (100 % CEM I; 70 % CEM I and 30 % slag) are compared to values calculated with the simulation model.

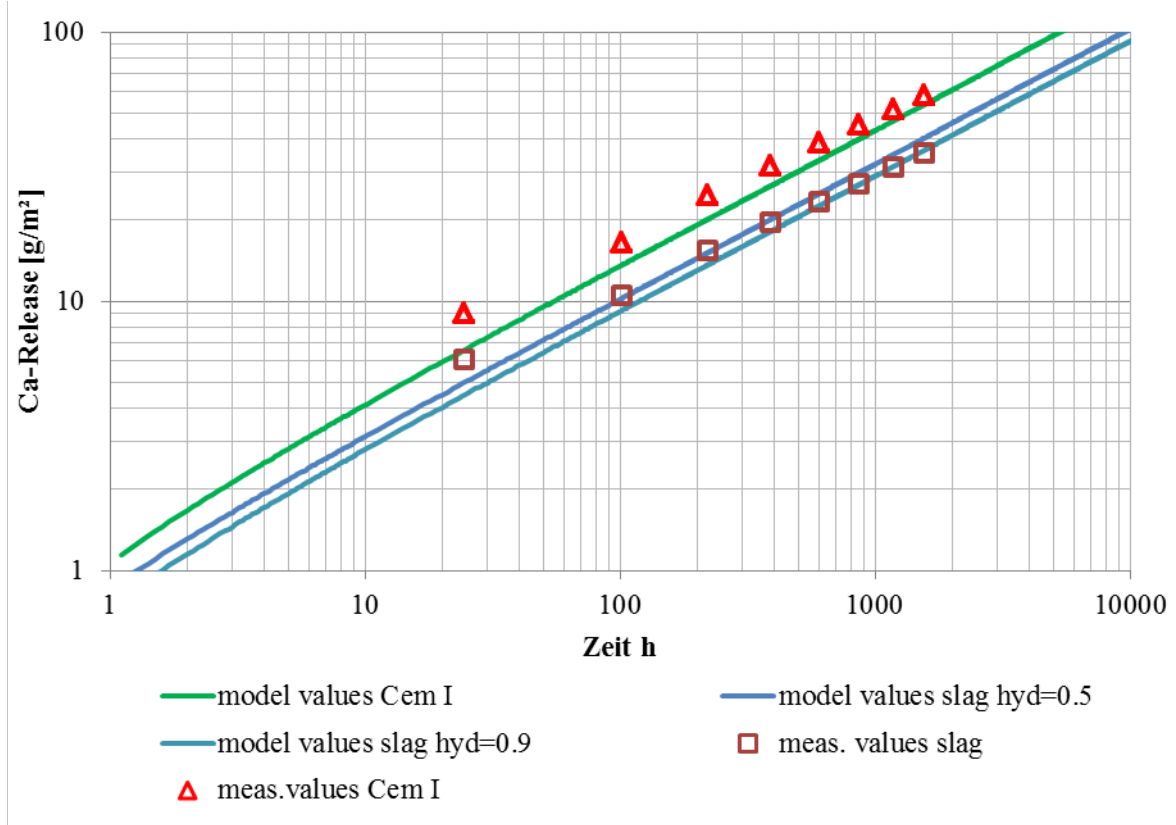


Figure 7: Comparison of Ca release over time calculated with the simulation model with the experimental results (determination according to the test procedure chap. 3.2). The model values for the CEM I / slag mortar are given for a simulated slag hydration degree of 0.5 and 0.9 (complete hydration = 1).

The figure shows very clearly, that the first few cycles of leaching report significantly high values. The measured values approach with increasing duration of leaching time to the model values. The higher the content of the cement clinker in the cement/mortar, the greater effect is pronounced.

A possible explanation would be a superposition of the diffusion at the beginning of the test series by a so-called “wash off” effect.

3 Experimental program

3.1 Preliminary remarks

Within a Bavarian research project new and already known binder compositions are studied to improve shotcrete mix-design regarding reduced calcium hydroxide leaching and subsequently reduce precipitations. The project is conducted in three steps: Lab tests, sprayed mortar tests and finally shotcrete tests with promising mix-designs.

Estimating the real leaching rate is very complicated and a target of ongoing research. Therefore, a simple test was introduced to give a fast indication of the leaching potential of cement bound materials. Leaching is performed with demineralized water at room temperature and with 56 days old samples.

3.2 Test procedure

The leaching behavior is tested according to the simple and straight forward testing procedure given by the Austrian code of practice "Festlegung des Reduzierten Versinterungspotentials" (Determination of the Reduced Potential for Precipitations) [9]. Concrete cores with a diameter of 50 mm and a length of 100 mm are drilled at an age of 56 days. Directly after drilling the cores have to be cleaned from drilling dust with water and immediately afterwards the leaching process has to be started.

The concrete core is embedded in a single closed test box and covered completely with demineralized water (= eluent). The ratio of eluent to solid is 4. The volume of air in the box is limited to less than 1000 ml.

The leaching process is divided into three cycles:

1. cycle: 24 h ± 1 h embedded
2. cycle: 48 h ± 2 h embedded
3. cycle: 120 h ± 4 h embedded

After each cycle, the leachate has to be decanted so that solid residuals remain at the bottom of the box. For the next cycle, the concrete core is embedded again with demineralized water.

In the leachate the electrical conductivity and the pH-value are measured. For the measurement of the calcium concentration in the leachate, the whole leachate is acidulated to a pH value of 3.0 to 4.0 to avoid effects of carbonation of dissolved calcium hydroxide.

The sum of the leached amount of calcium is calculated for the three cycles and expressed in kg/to (kg Calcium per ton of concrete). The medium value of the two cores tested gives the calcium release (Ca-Release) of the investigated concrete in kg/to [9].

The Ca-Release of shotcrete mix-designs with more than 400 kg/m³ Ordinary Portland Cement is usually higher than 1.0 kg/to. In Austria several tunnels have already been sprayed with reduced cement content (e.g. 280 kg/m³ CEM I 52.5 R and 140 kg/m³ AHWZ¹) to achieve a Ca-Release of 0.7 kg/to and sufficient early strength development of the shotcrete.

¹ AHWZ = aufbereitete hydraulisch wirksame Zusatzstoffe: Processed hydraulic additions for concrete production, usually a mixture of specially processed fly-ash with slag and limestone powder according to Austrian standard OENORM B 3309 [11]

4 Results from leaching tests

4.1 Lab tests

The basis for testing different mix-designs was a reference-mix with a content of 450 kg/m³ cement, 150 kg/m³ quartz powder, a w/c of 0.52 and quartz sand with a maximum grain size of 5 mm (Figure 8, left).

Further investigations concentrated on the influence of the reduction of cement content and adding different types of supplementary cementitious materials (SCM) (Figure 8, center). Differences of the mortar consistency were adjusted with a superplasticiser.

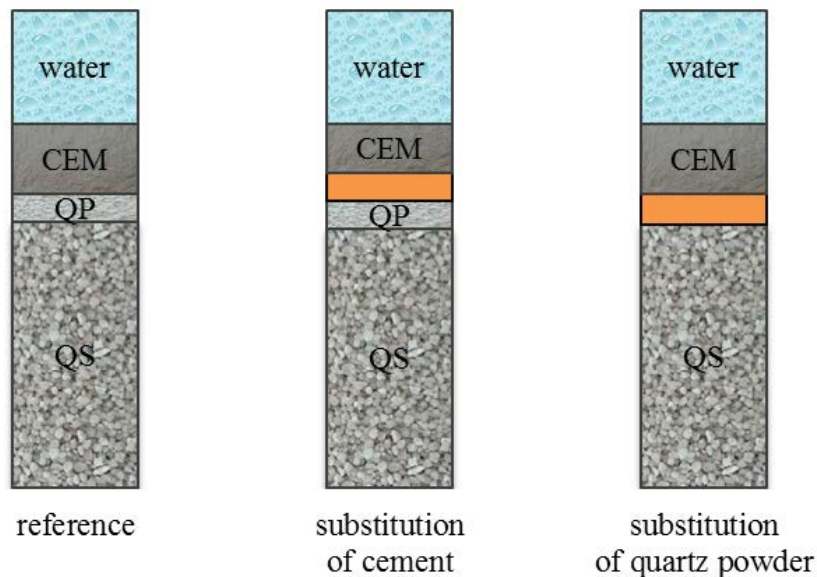


Figure 8: Schematic representation of mix-designs with different binder compositions

Results from these tests show that the reduction of Ca-Release compared to the reference-mix is obvious by replacing part of cement with pozzolanic or latent-hydraulic materials (Figure 9). The Ca-Release can be reduced by approximately 35 % when replacing 30 % of cement with SCM (AHWZ, fly-ash, slag). With highly reactive micropozzolan (HRM) a replacement of 15 % of cement leads to a reduction of the Ca-Release of 55 % with an amount of just 0.43 kg/to.

From these results it can be deduced that the reduction of cement content (and therefore also clinker content) in the binder leads to a reduction of the Ca-Release.

Samples of this series were again tested after one year storage. The results of the leaching test on these samples are shown in Figure 10. Compared to the samples tested at an age of 56 days, a further reduction of the Ca-Release is observed (e.g. AHWZ, fly-ash). This reduction can be contributed to further reaction of calcium hydroxide with the supplementary cementitious materials, especially in case of fly ash and AHWZ.

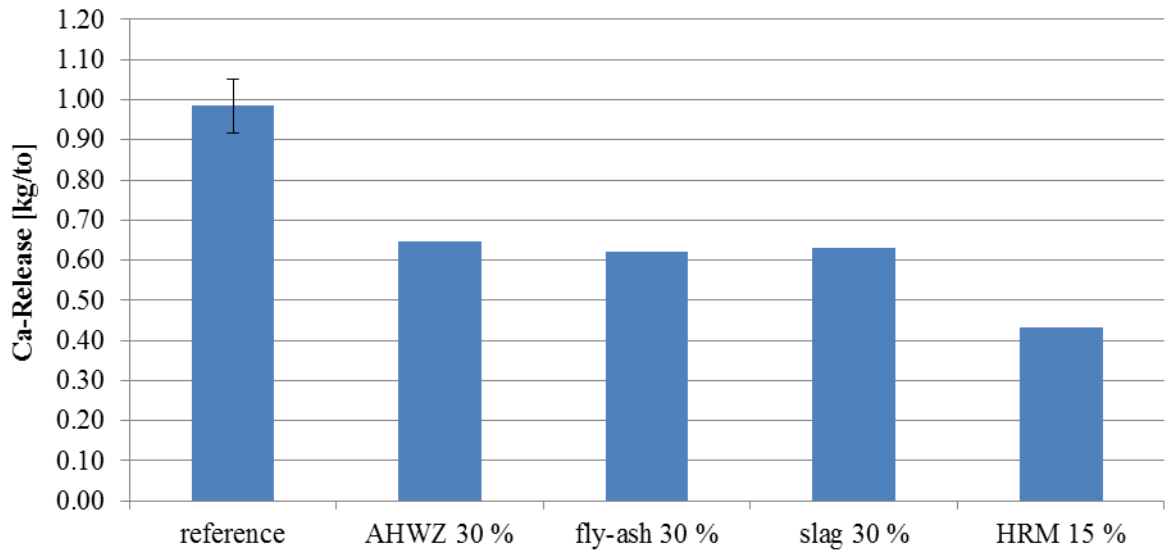


Figure 9: Ca-Release from mortars with different binder compositions (substitution of cement)

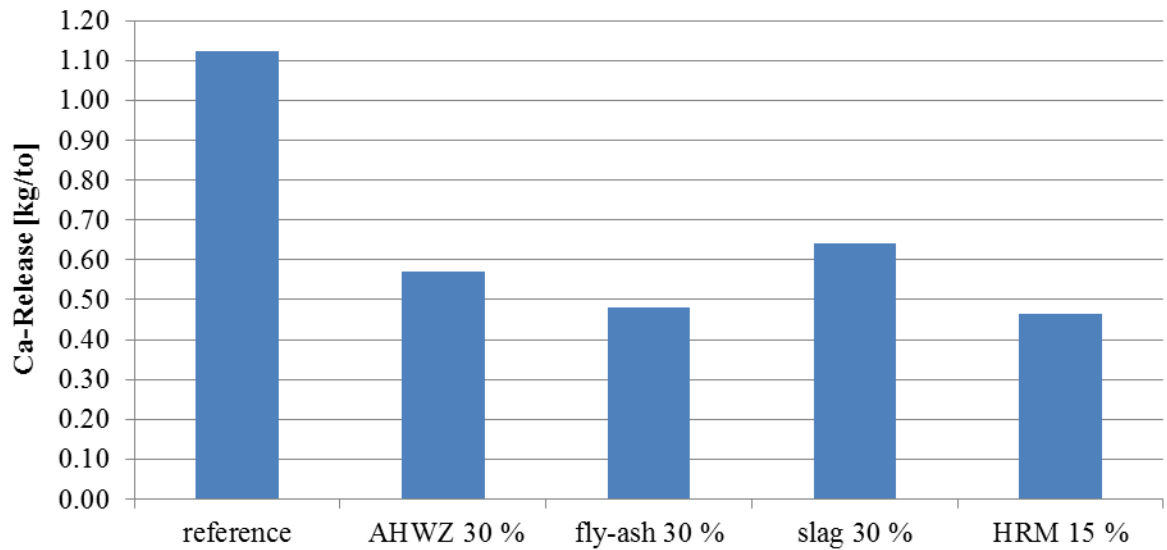


Figure 10: Ca-Release from mortars with different binder compositions (substitution of cement, storage time one year)

In a next series the influence of cement reduction and altering water/cement ratio was studied. The cement content in the mix was reduced and replaced with quartz powder. The water content was kept constant and hence increasing the w/c ratio (from 0.52 to 0.59, 0.67 and 0.87) (Figure 11).

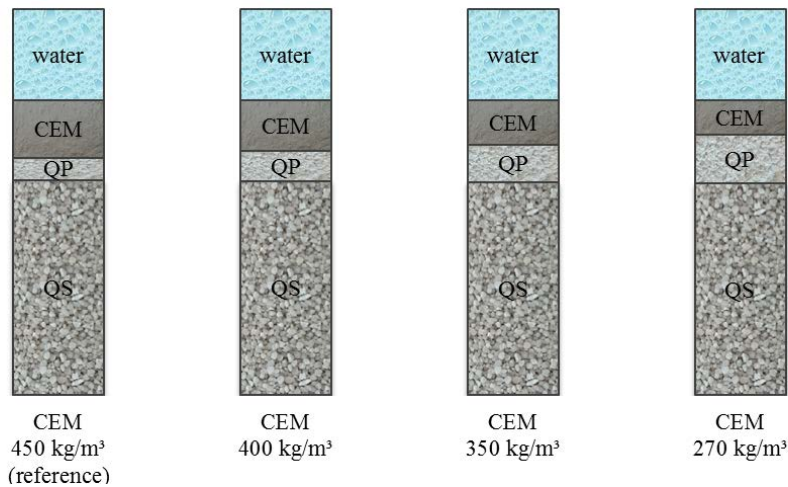


Figure 11: Schematic representation of mix-designs with reduced cement content and constant water content

From the results it can be seen that increasing the w/c ratio to 0.59 results in a lower Ca-Release compared to the reference mix (Figure 12). The effect of cement reduction is higher than the effect of increasing the w/c ratio. The increase of w/c to 0.67 leads to a higher Ca-Release compared to w/c of 0.59, although cement reduction is higher. Further increase of w/c to 0.87 gives further increase of Ca-Release, which is already close to the Ca-Release of the reference mix. Summarizing the increase of w/c ratio and hence the porosity superimposes the reduced Ca-Release which can be gained from reduced cement content.

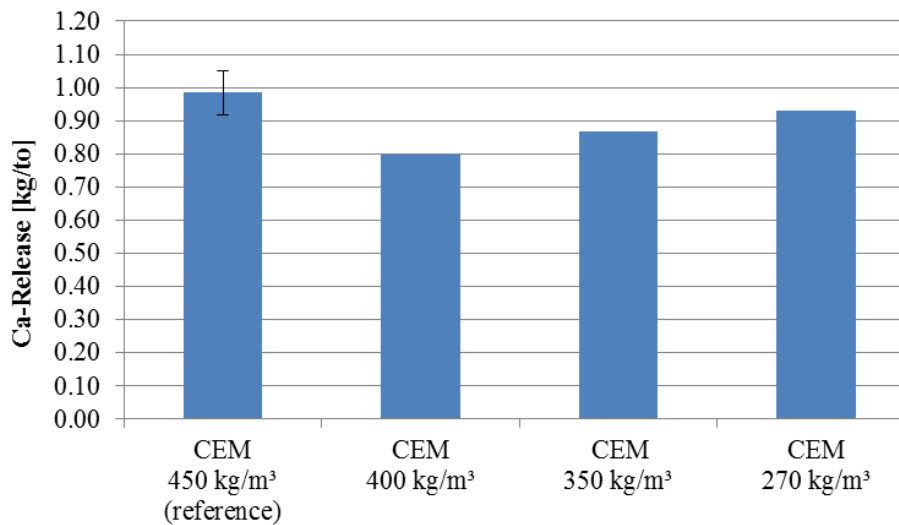


Figure 12: Ca-Release from mortars with reduced cement content and constant water content

The influence of reduced cement content was further investigated but without increasing w/c ratio. The w/c ratio was kept constant at 0.52 (Figure 13).

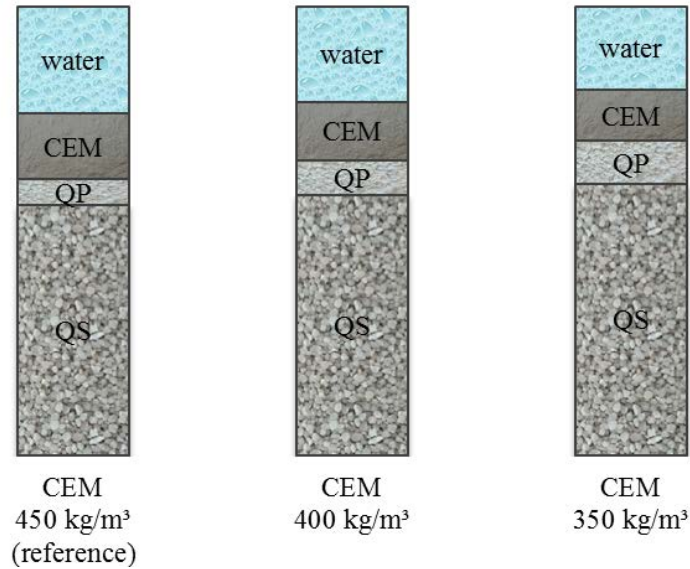


Figure 13: Schematic representation of mix-designs with reduced cement content and constant w/c ratio

The results from these tests are shown in Figure 14. When keeping the w/c ratio constant the reduction of cement content in the binder leads to clear reduction of Ca-Release compared to the reference mix.

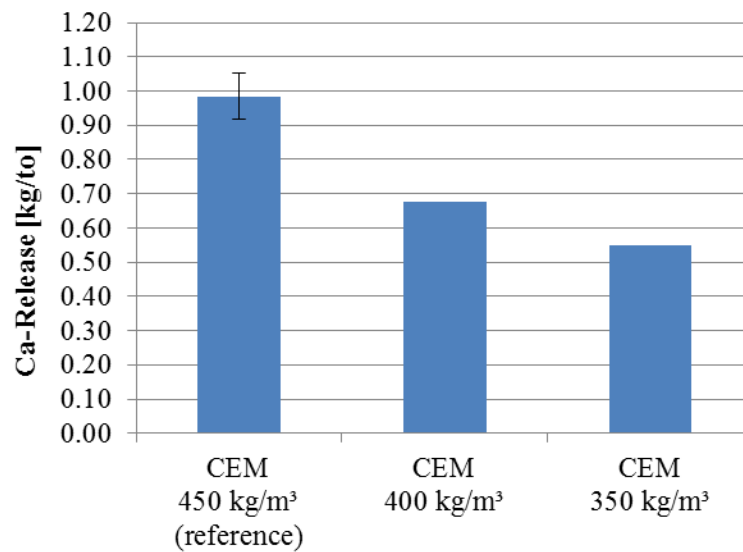


Figure 14: Ca-Release from mortars with reduced cement content and constant w/c ratio

In a further test series the cement content was kept constant (450 kg/m^3) and the quartz powder was replaced by AHWZ, fly-ash and slag (Figure 8, right). The results are given in Figure 15 and it can be seen that the substitution of the quartz powder with supplementary cementitious materials leads to a reduction of Ca-Release compared to the reference mix with quartz powder. Although the samples had the same cement content, there are quite differences in Ca-Release. This demonstrates that also reaction of the SCM with calcium hydroxide combined with a filling effect influences the rate of Ca-Release.

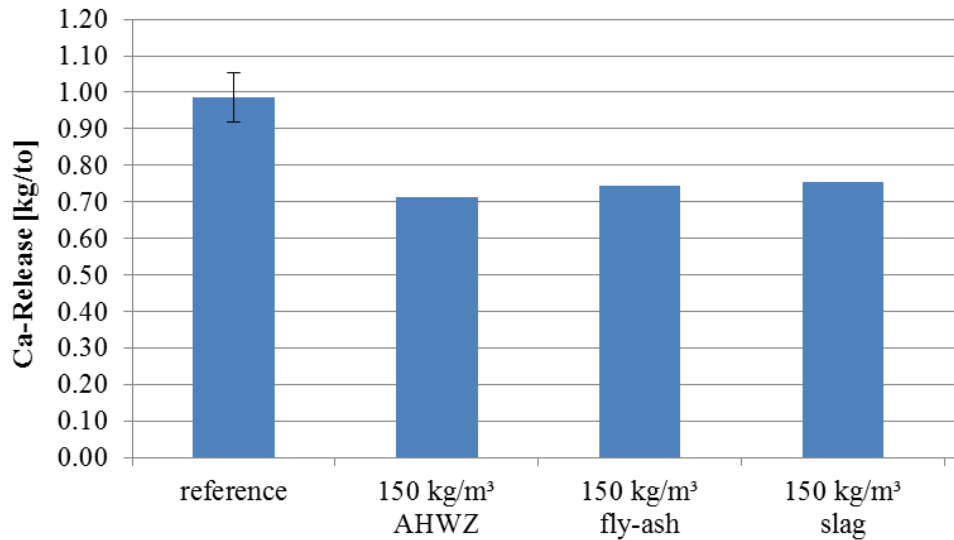


Figure 15: Ca-Release from mortars with different binder compositions (substitution of quartz powder)

4.2 Sprayed mortar tests

Successful combinations from the lab tests were further investigated with sprayed mortars to examine the influences resulting from spraying and the addition of accelerator.

Comparison of the results from the leaching tests give good agreement between samples from lab tests and sprayed mortar samples with same mix design, but the use of accelerator (Figure 16).

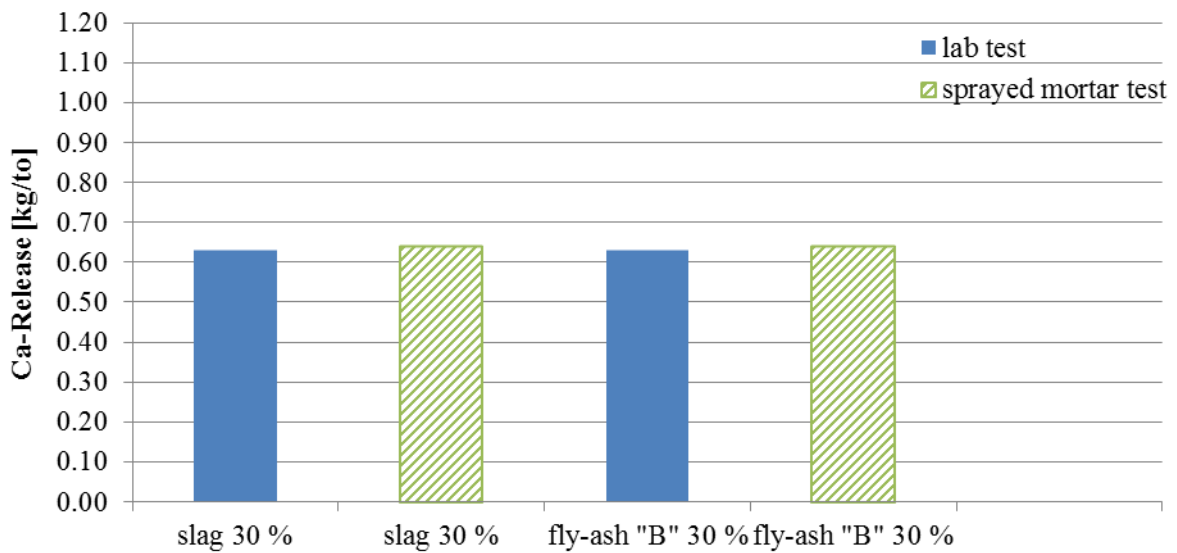


Figure 16: Comparison of Ca-Release from lab samples with sprayed mortar samples of same mix design

4.3 Shotcrete tests

Shotcrete tests were carried out with three different mix designs (Table 1 and Table 2). The binder composition of the reference mix was varied by reducing cement content and increasing SCM content.

Table 1: Shotcrete mix-design

	reference	AHWZ	slag
CEM I 52.5 N [kg/m ³]	380	280	280
AHWZ [kg/m ³]	40	140	---
slag [kg/m ³]	---	---	140
sand 0/4 [kg/m ³]	1227	1217	1224
aggregates 4/8 [kg/m ³]	524	520	523
total water content [kg/m ³]	190	190	190
accelerator [%]	7.7	7.0	7.0

Table 2: Characteristics of binders

	CEM I 52,5 N	AHWZ	slag
density [kg/dm ³]	3,1	2,7	2,9
Blaine value [cm ² /g]	4634	4300	3153
activity index (28 d) [%]	---	95	---
C ₃ A [%]	10	---	---

The early strength development of the three shotcrete mixtures is shown in Figure 17. The reference mix achieves early strength class J3. But also the mixtures with reduced cement content and increased SCM content exhibit early strength development class J2, which is sufficient for the majority of shotcrete applications during tunnel lining.

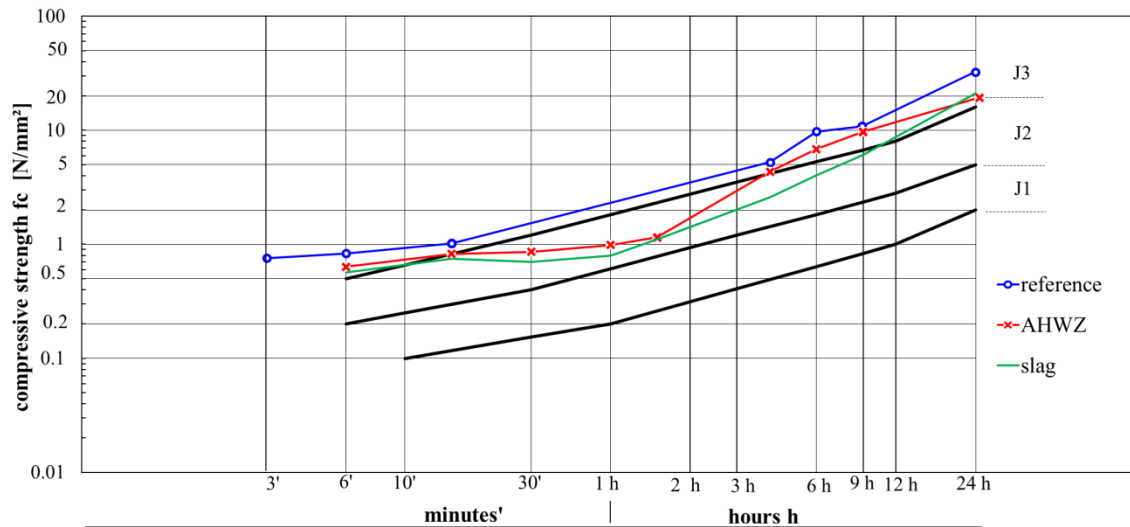


Figure 17: Early strength development of reference mix-design and mix-designs with AHWZ and slag

The results from leaching tests are not yet available. But it can be stated that in Austria shotcrete mix-designs with Portland Cement and AHWZ are already state of the art to reduce Ca-Release and hence the potential for precipitations. As mentioned earlier a Ca-Release of 0.7 kg/to can be achieved.

5 Summary and outlook

Within a Bavarian research project, the leaching behavior of different shotcrete mix-designs was investigated to reduce leaching of calcium hydroxide and thus minimizing the precipitation potential for the tunnel drainage system. Reductions in maintenance work cost will be the result of these investigations.

Results from lab tests and sprayed mortar tests show that a reduction of Ca-Release is possible by replacing part of the cement content with supplementary cementitious materials. On the one hand, the reduction of the Ca-Release is caused by the lower content of clinker in the binder. On the other hand also chemical reactions and filling effects result in a more dense matrix.

Based on those results, promising mix-designs were selected for site tests. The early strength development of shotcrete using mix-design with reduced cement content and a higher amount of supplementary cementitious material (e.g slag, AHWZ) reached early strength class J2. The leaching tests are not ready yet.

In Austria several tunnels have already been sprayed using reduced clinker content and AHWZ with sufficient early strength development and a Ca-Release below 0.7 kg/to.

The Ca-Release was investigated according to the Austrian Code of Practice “Festlegung des Reduzierten Versinterungspotentials (Determination of the Reduced Potential for Precipitations)”. In general it is a simple and reliable test method. Further studies are required in order to determine all influencing factors on the leaching test results and to optimize the test procedure.

Acknowledgement

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