## INFLUENCE OF SODIUM CHLORIDE ON ASR IN HIGHWAY PAVEMENT CONCRETE

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#### Abstract

After the increase of ASR-damages on highway concrete pavements in Germany it could be proved in several studies that the application of sodium chloride (NaCl) as deicing agent can trigger and accelerate ASR in concrete. A review of existing studies revealed, however, that there is no consistently accepted explanation about how NaCl influences the ASR.

In the present study, experiments were performed to elucidate the mechanism and to clarify contradictions within existing theories. The findings show that an external application of NaCl to concrete does not result in an increase of the pH in the pore solution. However, there are indications that the presence of NaCl promotes the dissolution of silica directly, i.e. beyond the influence coming from the pH. Further, the formation of chloroaluminates as FRIEDEL's salt turned out to be an accompanying but not a required reaction for an ASR in concrete exposed to externally applied NaCl.

Keywords: highway pavement concrete, sodium chloride, external alkalis, mechanism

## 1 INTRODUCTION

In the late 1990s, an increasing number of ASR-damaged concrete highway pavements occurred in Germany although the existing guideline for preventing ASR in concrete, first released in 1974, was strictly followed [1]. Affected highway sections showed first signs of ASR after about 8-15 years in service, i.e. after half the intended service life of 30 years at the latest. The high amount of highway pavement concrete (nearly 50 %) on the total number of ASR-damaged structures led to the suspicion that special mechanisms promote the ASR in pavements. Among others, it was focused on the influence of NaCl [e.g. 2,3,4,5] as the most used deicer worldwide and quickly a link could be found (Figure 1). The underlying mechanism, however, does not seem to be fully understood.

The influence of NaCl on ASR has been studied frequently since the 1970s. LOCHER and SPRUNG suggested that NaCl can only be active for an ASR as NaOH, for what the Cl- ions need to be bound in cement hydration products [6]. CHATTERJI et al. showed that mortar bars gave much higher expansions when stored in a solution of alkali salts than of NaOH (Figure 2), suggesting a direct influence of the alkali salts not related to a transformation into NaOH [7]. It was concluded that contrary to NaOH, NaCl does not lower the  $Ca^{2+}$  concentration in the pore solution and the higher the  $Ca^{2+}$  concentration the lower the diffusion of dissolved silica out of the aggregate grains what consequently results in higher expansion pressures [8]. A series of studies from KAWAMURA et al. clearly showed the accelerating effect of NaCl on ASR and linked the mechanism to a direct influence of the Cl- ions [9,10,11,12]. BÉRUBÉ and FRENETTE found that NaCl will only exacerbate ASR in concrete with a high alkali content, while for low-alkali cements NaOH is more severe [13]. It was concluded later that low-alkali cements are sufficient to avoid ASR in concrete exposed to NaCl, but the role of expansive chloroaluminates should be studied further [14]. SIBBICK and PAGE concluded that a supply of NaCl to concrete result in a formation of FRIEDEL's salt (C3A·CaCl2·10H2O) what increases the NaOH concentration in the pore solution and finally accelerates the ASR, also in concrete with a low alkali content [15,16]. SHAYAN found that a higher expansion for concrete exposed to NaCl solution is related to expansive chloroaluminates and ettringite rather than ASR [17]. Later, BROWN and BOTHE suggested that a formation of calciumoxychlorides result in an increase of the pH accelerating the ASR [18] what could not be confirmed, however, in a study from HOOTON and JULIO-BETANCOURT [19].

Overall, most of the studies showed that an external supply of NaCl can trigger and accelerate ASR in concrete but no consistent mechanism could be found so far. In the present paper, the most important findings from recent studies in [20,21] are briefly summarized, allowing to propose a new approach that would also explain and unify many findings from earlier studies.

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## 2 MATERIALS AND METHODS

## 2.1 General

The influence of NaCl on different concrete constituents was investigated by storing samples of cement and C-S-H paste, portlandite, ettringite, amorphous silica and strained quartz separately in different solutions at 45 °C (Table 1). Furthermore, long-term dissolutions tests on granodiorite samples in model pore solution at 8, 25 and 45 °C were started to investigate the silica dissolution behaviour in presence of NaCl in more detail (Table 2). Solutions and solids were analysed periodically and subsequent thermodynamic calculations were done.

## 2.2 Materials

Lab-grade Ca(OH)<sub>2</sub>, NaCl, KOH, ettringite and amorphous SiO<sub>2</sub> were used. The cement paste samples were made from two CEM I 42.5 N with a Na<sub>2</sub>O<sub>eq</sub> of 0.54 wt% and 0.76 wt% respectively. The C-S-H paste samples were obtained by hydration of lab-made C<sub>3</sub>S. Strained quartz grains were collected from a sample of an alkali-reactive gravel. The cement and C-S-H paste samples (w/b = 0.5) were used after a hydration of 28 days at 20 °C. Except the powdered compounds Ca(OH)<sub>2</sub> and ettringite, all other samples were used with a grain size of 2.5-5.0 mm. The water was double distilled and boiled to remove dissolved CO<sub>2</sub>.

The samples (2.0 g) of the cement and C-S-H paste,  $Ca(OH)_2$  and ettringite were stored separately in NaCl-solutions (40 ml) of different (0, 0.05, 0.3, 1.5, 2.5 mol/l) concentration. The strained quartz and amorphous SiO<sub>2</sub> samples (2.0 g) were stored in KOH-solutions (40 ml) with a pH of 13.9 and different (0, 0.05, 0.3, 1.5, 2.5 mol/l) concentrations of NaCl as well. Where reasonable, the model systems were prepared with (1.0 g) and without solid Ca(OH)<sub>2</sub>.

For every analysis, an individual sample was prepared to avoid changes in the solution/solid ratio over time. All samples were prepared in a  $N_2$ -filled glove-box to avoid carbonation, sealed airtight in plastic vials, subsequently discharged from the glove-box and stored at 45 °C over water for up to 3 months. All vials were shaken by hand 5 times a week.

Also, long-term dissolution tests for a 3-year period were started with crushed (0.1-0.5 mm) granodiorite samples (15 g) in KOH-solution (60 ml) at a pH of 14 and Ca(OH)<sub>2</sub> added (1.0 g) at different NaCl concentrations (0, 0.6, 2.5 mol/l). The granodiorite contains mainly quartz (25 wt%) and feldspars (58 wt%). The airtight sealed vials have been stored at 8, 25 and 45 °C over water.

# 2.3 Methods for assessment and analysis

## General

Prior to the analysis, the samples were placed back in the N<sub>2</sub>-filled glove-box to separate solution and solid by filtration (40  $\mu$ m). Solutions and solids were sealed airtight in plastic vials and discharged from the glovebox. Subsequently, the pH was measured immediately in the solutions prior to further preparation for the ICP-OES analysis. The solids were rinsed with isopropanol and acetone to remove residual solution and dried at 40 °C for 30 minutes prior to further processing for XRD and SEM/EDS analysis. Finally, thermodynamic calculations were done.

## Inductively coupled plasma-optical emission spectrometry (ICP-OES)

About 20 ml of the solutions were filtered (0.45  $\mu$ m), diluted (1:100) with nitric acid (1 %) and injected (100  $\mu$ l) in the argon plasma of the spectrometer (Perkin-Elmer, Optima 3000). The element concentrations of K, Na, Ca, Si, S and Al were determined. The detection limits range from 0.02  $\mu$ g/l for Ca to 30  $\mu$ g/l for S.

## X-ray powder diffraction (XRD)

The solids were gently ground in a corundum mortar until all particles passed the 40  $\mu$ m sieve. About 1 g of the powder was applied on a polyethylene sample holder. The X-ray diffractometer (Siemens, D-5000) uses Cu-K<sub>\alpha</sub> radiation of wavelength  $\lambda$ =0.154 nm. Diffractograms were recorded from 4-60° 20, in 0.05° 20 increments with 2.5 s counting time per increment.

#### Scanning electron microscope and energy-dispersive x-ray spectroscopy (SEM/EDS)

An environmental scanning electron microscope (Philips, XL 30 ESEM-FEG) equipped with EDS-detector was used to examine single phases and to determine their composition. The operating conditions ranged between 25-10 kV and 10-3 Torr. Additionally, an ultra-high resolution scanning electron microscope (Fei, NOVA<sup>TM</sup> NanoSEM 230) with EDS-detector was used to examine and analyse very small amounts of phases in high-vacuum mode at 3.5-7 kV. Since samples do not need to be coated for both microscopes, they can be studied in situ without artifacts.

#### Thermodynamic calculations

The thermodynamic calculations were performed by using PHREEQC [22]. The calculations support and extend the experimental results and provide essential information about the possibility of chemical reactions in the aqueous solutions studied. In order to account for the various interactions at high ionic strengths, the ion-interaction approach according to PITZER was used for all calculations. The provided database *pitzer.dat* had to be extended largely by supplementary thermodynamic data for cement-based systems. A selection of reactions discussed in the following is listed in Table 3. The complete supplementary data set used for the calculations can be found in [20].

## 3 RESULTS

## Binder models

For Ca(OH)<sub>2</sub>, ettringite as well as the C-S-H and cement pastes, the addition of NaCl always resulted in a slight decrease of the pH (Figure 3). Up to a NaCl concentration of about 1.5 mol/l, the Ca concentration increased slightly, followed again by a decrease except for ettringite (Figure 4). For ettringite and the cement pastes, with increasing NaCl concentration there was an increase of the  $SO_4^{2-}$  concentration (Figure 5), accompanied by the formation of FRIEDEL's salt and the dissolution of ettringite as found by XRD.

FRIEDEL's salt was already found at 0.05 mol/l NaCl in the ettringite samples with  $Ca(OH)_2$  and in the high-alkali cement pastes (Figure 6). In the low-alkali cement pastes, FRIEDEL's salt was found from 0.3 mol/l NaCl and in the ettringite samples without  $Ca(OH)_2$  not before 2.5 mol/l NaCl.

The formation of FRIEDEL's salt could be clearly confirmed by the SEM/EDS analysis in the corresponding ettringite and cement paste samples (Figure 7). Besides, amounts of Na and especially Cl were found by EDS in the C-S-H and cement paste samples (Figure 8). The formation of other new phases was not observed.

The results of the thermodynamic calculations correspond very well to the experimental findings (Figure 9, Figure 10) and provide the explanation for the course of the pH and the Ca concentration in the portlandite, ettringite and C-S-H paste samples which is related to the changing activities of the  $Ca^{2+}$  and  $OH^{-}$  ions when NaCl is added (Figure 11). Most important, in all calculations the pH does not increase by adding NaCl while a saturation and often oversaturation regarding FRIEDEL's salt was reached (Figure 12). Furthermore, all the solutions proved to be clearly undersaturated regarding any of the considered Ca/Cl-based compounds (Figure 12).

#### Aggregate models

For amorphous SiO<sub>2</sub>, the pH decreased significantly, especially when NaCl was added to the model pore solution (Figure 13). After a slight increase, the Si concentration decreased with increasing NaCl concentration while it is basically lower when Ca(OH)<sub>2</sub> was added (Figure 14). For the strained quartz, the pH remains constant without the addition of NaCl but decreased slightly when NaCl was added. Again, the Si concentration shows a slight but more distinct increase first, followed by a decrease with the addition of NaCl while it is basically lower too when Ca(OH)<sub>2</sub> was added.

It was evident by the naked eye already that the amorphous  $SiO_2$  in presence of  $Ca(OH)_2$  had transformed into a gel phase. The SEM/EDS analysis showed that the gel contains microcrystalline C-N/K-S-H phases (Figure 15). Without  $Ca(OH)_2$  and NaCl, the amorphous  $SiO_2$  was merely dissolved. When NaCl was added, however, a new phase was formed that turned out to be a completely amorphous N/K-S-H gel (Figure 16). For the strained quartz samples with  $Ca(OH)_2$  and a NaCl concentration of 2.5 mol/l, the SEM/EDS analysis showed microcrystalline C-N-S-H phases on the quartz surface (Figure 17). For the strained quartz samples without  $Ca(OH)_2$  and 2.5 mol/l NaCl, amorphous C-N-S-H phases were found (Figure 18).

It seems worth noting that the thermodynamic calculations for the studied silica systems does not provide reasonable results, e.g. much higher Si concentrations than measured were obtained, suggesting a lack of thermodynamic as well as kinetic data for the dissolution of silica in aqueous solutions with a high pH.

#### Long-term dissolution tests

Based on field experience, the granodiorite is highly alkali-reactive as proved with the ASR performance test (Figure 1). For all temperatures used, the granodiorite samples stored for about 2.5 years only showed a low and nearly constant Si an Al concentration when no NaCl was added. By adding NaCl (0.6 mol/l), however, an clear increase of the Si and Al concentration occurred at 45 °C after about 16 months (Figure 19, Figure 20). At 8 and 25 °C, no such increase could be observed so far. Also, for 2.5 mol/l NaCl no increase of the Si and Al concentration could be found.

#### 4 DISCUSSION

The findings show that an addition of NaCl to saturated solutions of portlandite with or without ettringite, C-S-H and cement paste as well does not result in an increase of the pH what corresponds to other studies [23,24]. This becomes clearer in combination with the thermodynamic calculations that show an undersaturation regarding the considered Ca/Cl-compounds and complexes respectively. But a formation of at least one of these would be necessary to remove  $Ca^{2+}$  from the solution and trigger a further dissolution of portlandite, driven by its effort to maintain the equilibrium with the solution, what would release additional OH- and finally increase the pH. The formation of FRIEDEL's salt could be confirmed as often reported [14-17] but is related to the transformation of ettringite as indicated by the release of SO42- (Equation 1). This would promote a delayed ettringite formation as sometimes accompanied indeed by an ASR in concrete pavements. But since no Ca<sup>2+</sup> is consumed by this reaction, no further dissolution of portlandite and consequently no release of additional OH<sup>-</sup> will occur. Only a formation of FRIEDEL's salt from C<sub>3</sub>A, C<sub>4</sub>AF and alike would bind Ca<sup>2+</sup> and Cl<sup>-</sup> at once, resulting in a dissolution of portlandite and finally in an increase of the pH. This happens if NaCl is added straight to the mixing water, as previous studies already showed [25]. Hence, completely different mechanisms run when NaCl is added to the mixing water or when it is applied externally to hardened concrete.

## $C_{3}A \cdot 3C_{4}SO_{4} \cdot 32H_{2}O + 2Na^{+} + 2CI^{-} = C_{3}A \cdot C_{4}CI_{2} \cdot 10H_{2}O + 2Ca^{2+} + 2Na^{+} + 3SO_{4}^{2-} + 22H_{2}O$ (1)

The absence of an pH increase is the reason for the less severe impact of NaCl on ASR compared to deicers based on alkali acetates and formates as shown earlier [20,26]. Hence, speed and extent of the silica dissolution in concrete exposed to NaCl solutions is basically controlled by the cement-based pH. However, the findings show that the presence of NaCl promotes the dissolution of silica directly, beyond the influence coming from the pH. This is in agreement with other studies from CHATTERJI et al. [7] who suggested a more direct influence of alkali salts on ASR and especially from KAWAMURA et al. [9,10] who more precisely suggested a direct influence of the Cl- ions. These views are supported by studies from DOVE et al. showing an significant increase of the silica dissolution rate in NaCl solutions, even for a pH below 12 [27]. The mechanism assumed is a formation of  $\equiv$ SiO-Na<sup>+</sup> complexes at the silica surface resulting in higher silica dissolution rates [27]. Similarly, ZHANG and LIU concluded recently that the adsorption of alkali metal ions as Na<sup>+</sup> on the silica surface weakens the Si-O bond and accelerating the hydrolysis reaction [28]. In a study from DRESSLER et al., the formation of an aqueous NaHSiO<sub>3</sub> complex was proposed that again would result in an increase of the silica solubility [29,30]. However, the more severe impact of NaCl compared to NaOH as often reported [e.g. 7,9] cannot be explained by a solely Na-driven mechanism. The anion (Cl-), as already assumed by KAWAMURA et al., seems to play a role too. Obviously there is a non-linear relationship resemble the "salting-in/out" effect [31,32,33] since for all the systems with SiO<sub>2</sub> studied here, the Si concentration increases initially with increasing NaCl concentration, followed again by a decrease. Also, besides silica, the dissolution of the feldspars seems to be affected as indicated by the increasing Al concentration. Further research is in progress to elucidate this mechanism in more detail.

Based on the SEM/EDS analysis of the amorphous silica and quartz samples respectively it is evident that ASR products had formed. If Ca(OH)<sub>2</sub> was added, a microcrystalline C-N/K-S-H phase was formed, without Ca(OH)<sub>2</sub> an amorphous N/K-S-H gel was found. It is to emphasize that the only source of the incorporated Na in these phases was the NaCl added. Further, the ASR products had formed without a prior binding of the Cl<sup>-</sup> ions into FRIEDEL's salt since its formation was not possible due to the absence of corresponding Ca-Al-phases. Hence, a formation of FRIEDEL's salt is an accompanying but not a required reaction for an ASR in concrete exposed to externally applied NaCl. The fate of the Cl<sup>-</sup> ions is to remain in the pore solution as shown in [34], to be adsorbed on C-S-H phases as found by the SEM/EDS analysis and proved in [35] and/or to be bound pro-rata in FRIEDEL's salt and ASR products respectively.

The vital role of Ca(OH)<sub>2</sub> is to resupply OH<sup>-</sup> ions that are consumed by the dissolution of silica and to provide Ca<sup>2+</sup> ions to form ASR products. Hence, even in concrete with low-alkali Portland cement (CEM I) the pH is maintained high enough (> 13) to dissolve silica, although it takes longer compared to concrete with high-alkali cement at a very high pH (~ 14). If NaCl is applied externally, the dissolution of silica is additionally promoted and extra Na<sup>+</sup> ions are available to form ASR products. Thus, ASR in concrete applied to external NaCl may be delayed but not prevented permanently when low-alkali cement (CEM I) is used. The duration of the delay depends on the alkali content of the cement too, but primarily on the alkali-reactivity of the aggregates and the intensity, i.e. amount and concentration, of the externally supplied NaCl.

## 5 CONCLUSIONS

Experiments were performed to elucidate the mechanism of ASR in highway pavement concrete exposed to externally applied NaCl. The conclusions derived correspond to field experience and other studies and extend existing theories:

- An external application of NaCl to concrete does not result in an increase of the pH in the pore solution. Hence, speed and extent of the silica dissolution is basically controlled by the cement-based pH. It was evident, however, that NaCl promotes the dissolution of silica directly, i.e. beyond the known influence coming from the pH. In order to elucidate the underlying mechanism in more detail, further research is in progress.
- A formation of ASR gel with Na<sup>+</sup> delivered from NaCl can occur without a formation of FRIEDEL's salt. Hence, the formation of FRIEDEL's salt in concrete exposed to NaCl solution is an accompanying but not a required reaction for an ASR. FRIEDEL's salt is formed from ettringite, releasing SO<sub>4</sub><sup>2–</sup> what consequently can increase the likelihood for a delayed ettringite formation later on.
- Finally, depending on the alkali-reactivity of the aggregates and the cement-based pH, lowalkali cements (CEM I) may delay the ASR more or less but cannot prevent it permanently in concrete exposed to externally supplied NaCl.

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	Composition of the model systems									
System	Ca(OH)2	Ettringite	C-S-H	SiO <sub>2</sub> (am.)	Quartz*	H <sub>2</sub> O	KOH solution (0.85 mol/l)	NaCl** (0-2.5 mol/l)		
Cement paste phases										
СН	×					×		×		
Ettringite + CH	×	×				×		×		
Ettringite		×				×		×		
C-S-H	×		×			×		×		
Cement paste										
CEM I <sub>high</sub>	cement paste (Na <sub>2</sub> O <sub>eq</sub> = $0.76 \text{ wt}$ %), w/c = $0.5$ , 28 d			.5, 28 d	×		×			
CEM Ilow	cement paste (Na <sub>2</sub> O <sub>eq</sub> = $0.54$ wt%), w/c = $0.5$ , 28 d ×					×				
Aggregates										
Silica + CH	×			×			×	×		
Silica				×			×	×		
Quartz + CH	×				×		×	×		
Quartz					×		×	×		

TABLE 1: Sample settings for the model systems.

\*predominantly strained quartz \*\*each system with 0, 0.05, 0.3, 1.5 and 2.5 mol/l respectively

TABLE 2: Sample settings for the granodiorite\* long-term (3-year) dissolution tests.

KOH solution	Concentration (mol/l)	1.0								
KOTT solution	Sample mass (g)					60		45 0 0.6		
Ca(OH) <sub>2</sub>	Sample mass (g)					1.0				
Course lie site	Grain size (mm)	0.5 - 1								
Granodionte	Sample mass (g)					15	1 45			
Storage temperature (°C)		8			25			45		
NaCl concentration (mol/l)		0	0.6	2.5	0	0.6	2.5	0	0.6	2.5

\*25.1 wt% quartz, 45.1 wt% plagioclase, 13.0 wt% orthoclase, 10.0 wt% biotite, 3.8 wt% chlorite, 3.0 wt% muscovite

TABLE 3: Selection\* of supplementary data (25 °C) for the thermodynamic calculations.

Phase	Formula	Reaction	log K	Reference
Calcium chloride	CaCl <sub>2</sub> (s)	$Ca^{2+} + 2Ch$	11.79	[22]
Calcium chloride hydrate	CaCl <sub>2</sub> ·H <sub>2</sub> O <i>(s)</i>	$Ca^{2+} + 2Cl^- + H_2O$	7.85	[36]
Calcium chloride dihydrate	$CaCl_2 \cdot 2H_2O(s)$	$Ca^{2+} + 2CI^{-} + 2H_2O$	7.95	[36]
Calcium chloride tetrahydrate	$CaCl_2 \cdot 4H_2O$ (s)	$Ca^{2+} + 2CI^{-} + 4H_2O$	5.36	[36]
Calcium chloride hexahydrate	$CaCl_2 \cdot 6H_2O(s)$	$Ca^{2+} + 2CI^{-} + 6H_2O$	3.94	[36]
Calciumoxychlorid "1"	CaCl(OH) (s)	$Ca^{2+} + Cl^- + OH^-$	-0.67	[36]
Calciumoxychlorid "2"	$CaCl(OH) \cdot H_2O(s)$	$Ca^{2+} + Cl^- + OH^- + H_2O$	-2.51	[36]
Calciumoxychlorid "3"	$Ca_2Cl_2(OH)_2 \cdot H_2O$ (s)	$2Ca^{2+} + 2Cl^{-} + 2OH^{-} + H_2O$	-1.47	[37]
Calciumoxychlorid "4"	Ca4Cl2(OH)6·13H2O (s)	$4Ca^{2+} + 2Cl^{-} + 6OH^{-} + 13H_2O$	-15.29	[37]
Ettringite	Ca6Al2(SO4)3(OH)12:26H2O (s)	6Ca <sup>2+</sup> + 2Al(OH) <sub>4</sub> - + 3SO <sub>4</sub> <sup>2-</sup> + 4OH- + 26H <sub>2</sub> O	-44.91	[38]
FRIEDEL's salt	Ca4Al2(Cl)2(OH)12·4H2O (s)	$4Ca^{2+} + 2Al(OH)_{4^-} + 2Cl^+ + 4OH^- + 4H_2O$	-28.2	[39]

\* the complete supplementary data set used for the calculations can be found in [20]



14 NaNO<sub>2</sub> 12-° 10 NaCl NaNO<sub>3</sub> .⊆ 8-Expansion 6 4 NoOH 2 Na<sub>2</sub>PO 0 8 12 16 20 Time in weeks

FIGURE 1: Expansions for concrete prisms, tested with the cyclic climate storage (described in [2-5, 20]) under exposure of solutions of different alkali salts [7]. different deicer solutions (0.6 mol/l) and water.



FIGURE 3: Measured pH (56 d) for the binder model systems as function of the NaCl concentration.



FIGURE 5: Measured S concentrations (56 d) for the binder model systems as function of the NaCl concentration.

FIGURE 2: Expansion of mortar bars stored in 3-molar



FIGURE 4: Measured Ca concentrations (56 d) for the binder model systems as function of the NaCl concentration.



FIGURE 6: XRD spectra (56 d) of the cement samples of system "CEM Ihigh" (E: ettringite, FS: FRIEDEL's salt).



FIGURE 7: CEM Ilow paste (56 d, 2.5 mol/l NaCl) with FRIEDEL's salt (centre).



FIGURE 8: CEM Ihigh paste (56 d, 2.5 mol/l NaCl) C-S-H phases with adsorbed Cl (EDS).



FIGURE 9: Calculated pH for some binder model systems as function of the NaCl concentration.



FIGURE 11: Ca<sup>2+</sup> and OH<sup>-</sup> activity for the system "CH" (exemplary) as a function of the NaCl concentration.



FIGURE 13: Measured pH (56 d) for the aggregate model systems as function of the NaCl concentration.



FIGURE 10: Calculated Ca concentrations for some binder model systems as function of the NaCl concentration.



FIGURE 12: Saturation indices (> 0 oversaturation, < 0 undersaturation) of phases for the system "Ettringite+CH" (exemplary) as function of the NaCl concentration.



FIGURE 14: Measured Si concentrations (56 d) for the aggregate model systems as function of the NaCl concentration.



Mic HV WD Mag Dat 10-CH2.5 KL 25K49.8 miss00x cssE - 2 µm - FIGURE 15: Microcrystalline C-N/K-S-H phases (EDS) in the system "Silica+CH" (2.5 mol/l NaCl, 84 d).



 XL [25 kV]10,1 mm[500 x]GSE
 \_\_\_\_\_\_50 µm\_\_\_\_\_

 FIGURE 16: Amorphous N/K-S-H phases (EDS) in the system "Silica" (2.5 mol/l NaCl, 84 d).



FIGURE 17: Microcrystalline (flaky) C-N-S-H phases (EDS) in the system "Quartz+CH" (2.5 mol/l NaCl, 84 d, NanoSEM).



P TO KW 10000 k 8 smm LVD 0.47 nk 3 s4E 4 kar 2 b 2 5 k

FIGURE 18: Amorphous C-N-S-H phases (EDS) in the system "Quartz" (2.5 mol/l NaCl, 84 d, NanoSEM).



FIGURE 19: Measured Si concentrations for the granodiorite long-term dissolution tests in model pore solution with different NaCl concentrations at 45  $^{\circ}$ C.

FIGURE 20: Measured Al concentrations for the granodiorite long-term dissolution tests in model pore solution with different NaCl concentrations at 45  $^{\circ}\mathrm{C}.$