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The Environmental Degradation of Cement-Based Materials Due to Alkali-Silica Reaction: Case Studies

C. S. Paglia[1*], S. Antonietti[1] and G. Corredig[1]

[1]*Institute of Materials and Construction, Supsi, V. Flora Ruchat 15, CH-6850 Mendrisio, Switzerland*

*Correspondence author
C. Paglia,
Institute of Materials and Construction,
Supsi, V. Flora Ruchat 15,
CH-6850 Mendrisio,
Switzerland.

Abstract

The environmental degradation of infrastructures is widely widespread. Every material or combination of it is subjected to a specific type of deterioration, which can occur in combination with other damaging effects. Structures are subjected to physical, chemical, mechanical and biological attacks. The monitoring, the diagnostic and the restoration are expensive processes that often can be mitigated by a correct material planning and design. Concrete structures are affected by freeze / thaw attack, acid and water leaching and sulphate deterioration. Every mechanism takes place at different rates depending upon the concentration of the aggressive pollutants and the environmental parameters, such as the humidity and the temperature. Alkali-silica reaction is known to happen between the alkali content of the cementitious binders and the amorphous quartz-rich stone aggregates. It usually takes a relatively long time to occur. In this work, cableway piles exposed to adverse atmospheric condition on a mountain as well as a support wall of a freeway 80 meters high pile were investigated with respect to the microstructure, the residual expansion in a NaOH-rich solution and the damage. Expansive gel was found around some stone aggregates. This caused the formation of wide cracks. These latter created a net-like structure on the concrete surface and spalling of the concrete cover was observed. Immersion tests in an alkali-rich solution also exhibited a potential residual expansion of the concrete, which was in turn related to the microstructure and the mineralogy of the cementitious material. The humidity, the aggregates and the reactive alkalis interact on a long-term basis over 50 years and largely control the extension of the degradation. Even with widely opened cracks, the AAR reaction potential may not be still completely stopped. Repair mortar applied on concrete may act as a barrier against the reaction, but it is not be able to completely mitigate the AAR effect.

Keywords: concrete, degradation, cracks, alkali-silica reaction

Introduction

Concrete is a mineral material widely used in the construction. It can be considered durable, although the reaction between the hydroxyl ions of the Portland cement with the poorly crystalline or amorphous substances present in the stone aggregates may lead to Alkali Aggregate Reaction (AAR). In particular the alkalis of the cement react with the silica to produce a hygroscopic gel around the aggregates. This causes an expansion and cracking of the material and is responsible of many of the damage observed in concrete structures. Dams, roadways, walls, and other structures are affected by these phenomena, which can take some time to occur (Latifee, 2016, Thomas et al., 2012; Diamond, 1992) and can be severe (Bach et al., 1993; Islam & Ghafoori, 2011; Swamy, 1991). The effect of aluminum on the dissolution of silicates as well as a better characterization of the alkali-silica reaction products and the influence of the temperature and relative humidity are some of the recent findings (Leemann et al., 2021). Several procedures,

recommendations and tests were developed to assess the AAR susceptibility of cementitious materials (Mene´ndez et al., 2021; Rønning et al., 2021; Borchers et al., 2021; Borchers, 2021; Yamada et al., 2021). These are also important to optimize new concrete mixtures and avoid long-term damage.

An overview of the AAR presence on the infrastructure along the alpine and sub-alpine region in Switzerland indicated the damage to occur in a relatively long period of time and to be variable depending on the geographic region. The tensile strength and modulus of elasticity were more sensitive of the damage as compared to the compressive strength of the concrete (Merz et al., 2006). The restoration methods are multiple, but the efficacy not always good as expected (Durand, 2000), although the reaction may be lowered (Delaby et al., 2004). Surface protection systems were applied through hydrophobic agents, coatings, and impregnations, although

with controversial success (Durand, 2000; Fujii et al., 1989; Hamada et al., 2004). In fact, the water or humidity content of the internal part of the structures may not be eliminated. Furthermore, the crack bridging capability of the coating remains questionable for highly damaged artifacts. Epoxy-based crack injections are also used in some cases (Fiala, 2003), but they do not contribute to solve the humidity issue. Lithium salts are also used to reduce the damaging effects. They appear to form a non-expansive reaction product with the silica gels and protect the reactive aggregates (Barborak et al., 2004; Thomas & Stokes, 2004), at least the alkali silica reaction, not necessarily the alkali-carbonate formation. The elimination of the damaged concrete and the application of a new mortar may extend the service life of the elements (Durand, 2000).

The present work focuses on two case studies: a viaduct pile support wall and a cableway pile basement. The degradation of both elements is studied in detail with visual inspection, mechanical and durability tests, with the analysis of the microstructure and with the determination of the residual damaging potential. These two cases differently expose the infrastructure to the environmental conditions and highlight the difficulties of completely mitigating the AAR reaction also in surfaces coated with cementitious systems. In addition, widely opened cracked structures may still exhibit a potentially reactive AAR behaviour.

Experimental Procedure
A highway viaduct pile support wall and cableway basements placed on altitude covered with a protection mortar were investigated. Visual inspections, the crack opening index (Standard SIA 269/2, Maintenance of structural concrete, 2011), optical microscopy, the modulus of elasticity (Standard SIA 261/1 Concrete construction – complimentary specifications, 2019) were determined. The carbonation depth (Standard SN EN 14630, determination of carbonation depth in hardened concrete by the Phenolpthalein method, 2006) was measured by spraying a solution with 1000 mg of phenolphthalein and 70 g of ethanol and 100 ml deionized water of cylindrical broken concrete halves. The distance between the concrete surface and the pink coloured region is defined as the carbonation depth. The residual alkali aggregate reaction expansion was tested by immersing the concrete specimens 75 x 75 x 285 mm specimens in a NaOH solution with a concentration of 1 molar at 38°C. The variation in the sample length was measured with a digital comparator up to 6 months and the test method applied for the concrete (Standard EN 8520-22, Concrete aggregates, part 22, Method to evaluate the potential alkali-silica reactivity of the aggregates, 2020).

Results and Discussion

Pile support wall
The viaduct pile support wall was more than 50 years old and was placed at about 600 meters above sea level. The region was in the South part of the Alps. The wall exhibited a net-like crack pattern, typical for alkali-aggregate reactions (Fig. 1 left).
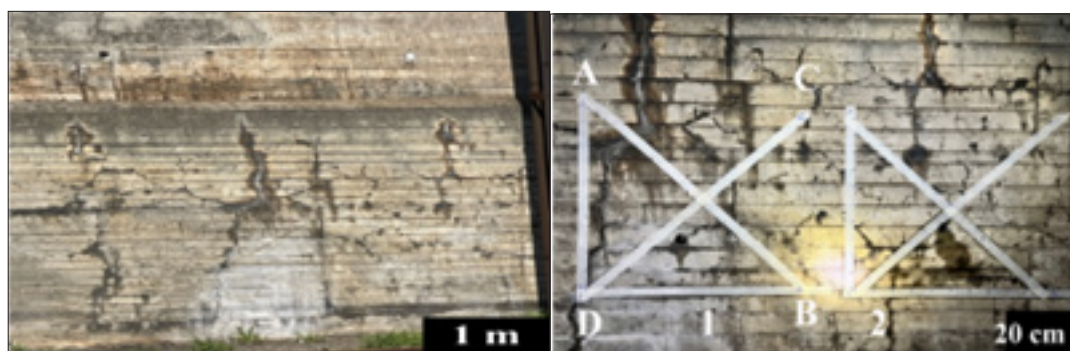
Figure 1: AAR damage with a crack pattern on the concrete wall. The opening reached several milimeters and salt crystallization was also seen (left). Crack opening index measurement pattern (right).

The crack opening index was measured in two regions (nr. 1, nr. 2) along specified directions (Fig. 1 right). The axis length varied from 1 meter to 1.4 meters and the number of cracks observed along the lines ranged from 2 to 8. The medium width ranged from 0.10 mm to 1.3 mm. The resulting indexes (RI) were 1.95 for the region 1 (Table 1 left) and 1.17 for the region 2 (Table 1 right). The data evaluation indicates a minor damage for the index RI ≤ 1. A medium damage can be assumed for $1 < RI < 3$ and a high damage for RI ≥ 3. In the present cases, a medium damage can be confirmed.

Direction	Crack width [mm]	Axis length [m]	N° cracks	Medium width [mm]	Cumulative width [mm/m]	Crack opening index [mm/m]
0 - B	0.1, 0.1, 0.1, 0.1	1	4	0.10	0.40	1.95
0 - A	2.2, 0.2, 1.5	1	3	1.30	3.90	
0 - C	2.2, 0.1, 0.1, 0.8, 0.2	1.4	5	0.68	2.43	
A - B	1.3, 0.2	1.4	2	0.75	1.07	

Direction	Crack width [mm]	Axis length [m]	N° cracks	Medium width [mm]	Cumulative width [mm/m]	Crack opening index [mm/m]
0 - B	0.4, 0.5, 0.2, 0.05, 0.05	1	5	0.24	1.20	1.17
0 - A	0.2, 0.5, 0.1, 0.1, 0.2, 0.05	1	6	0.19	0.15	
0 - C	0.5, 0.1, 0.05, 0.05, 0.1, 0.4, 0.2, 0.1	1.4	8	0.19	1.07	
A - B	0.3, 0.5, 0.3, 0.5, 0.1, 0.05	1.4	6	0.29	1.25	

Table 1: Medium crack width and crack opening indexes for the region 1 (top) and the region 2 (bottom).

The microstructure investigated with an optical microscope exhibits wide cracks partially filled with amorphous isotropic expansive siliceous gel caused by the alkali-aggregate reaction. A coarse quartz aggregate also shows a reaction edge.
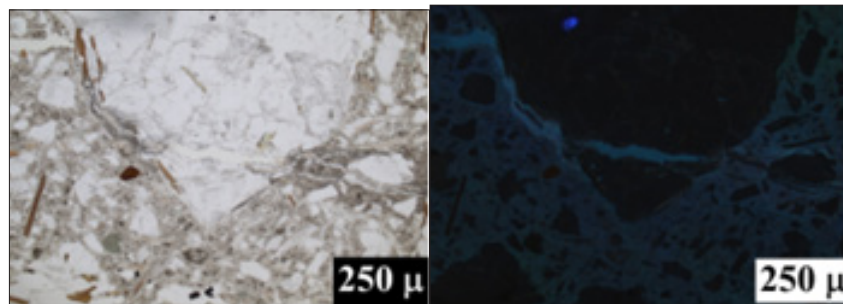
Figure 2: Microstructure of the concrete with reaction edges around a quartz aggregate. A crack penetrates across the aggregate. The microstructure was evaluated with an optical microscope with parallel Nichols (left) and with a fluorescent impregnation resin and investigated under ultraviolet light.

The cementitious matrix is relatively compacted. The cement binder exhibits a medium to high hydration grade. The aggregates are reactive. They mainly consist of quartz single crystals and quartz-feldspar rock aggregates. Micas as well as micritic calcareous rocks are relatively present. The AAR reaction shows a variable degree, while in some cases no reactions are observed. In some areas, the cracks are absent. And yet, no reaction margins are present around the aggregates and only a few crack openings < 5 mm are seen within the cementitious matrix, and rarely within the aggregates. In other regions, an initial AAR reaction is detected. On the other hand, some samples exhibit an advanced stage of AAR reaction with an extensive crack pattern. Some crack openings vary from 100-300μ to many millimeters. Some cracks are filled with amorphous expansive AAR reaction gel. Reaction margins are present around the aggregates and sometimes they are broken. The expansive forces lead to material detachment.

Cableway basements

The concrete basements of a cableway placed between 1400-1900 meters above sea level were 50 years old (Fig. 1). In order to further protect the structures, a mortar coating was applied on the concrete basements. This was done in particular for protection purposes, considered the harsh atmospheric condition at the altitude and the safety requirements for such a structure.

Figure 3: Cableway placed in altitude. Metallic structure supported by concrete basements.

The concrete basements exhibit a low carbonation with a general mean value of 2.2 ± 1.3 mm. A relatively low value considering the old age of the structures (Table 2). The carbonation coefficient is 0.3 [mm / year0.5]. The single values also indicate a very moderate carbonation. This may be due to the restoration mortar applied on the concrete basement, that during the years acted a protection barrier for the ingress of atmospheric CO_2. In addition, the altitude and the generally low temperature present during time keep the relative humidity at a high level, thus lowering the carbonation. In spite of the lower concrete cover as required from the current normative, the basements may still be able to width stand the carbonation process on a medium-long term basis.

Concrete basements				
ID	Sampling	Carbonation depth [mm]		
		Minimum	maximum	mean
1.1.1		1	2	1
1.1.2		1	3	2
1.1.3		1	3	2
4.1.D		3	4	4
4.2.S		4	7	5
5.1		1	2	2
5.4		1	2	2
6.1		1	2	1
6.4		1	5	3
7.1.S		1	2	1
7.2.D		1	2	1
Mean value and standard deviation				2.2 ± 1.3

Table 2: Carbonation values of the cableway concrete basements covered with a protection mortar.

During the placing works 50 years ago, the required concrete cover was 25 mm for structures directly exposed to cyclic atmospheric temperature and humidity changes. Today a concrete type C with compressive strength class C30/37 and exposition classes XC4, XF1, requires for the rebars a concrete cover of 40 mm. Consequently, the measured values are inappropriate. In fact, the mean concrete cover values range from 26.7 to 34.1 mm (Table 3).

Pile basement					
ID	Sampling	CF_{max} [mm]	CF_{min} [mm]	Mean CF [mm]	σCF [mm]
a	Pile basements	44	15	26.7	8.4
b		46	18	34.1	8.6

Table 3: Concrete cover mean values and standard deviations for some basements. CF_{max}: max. concrete cover; CF_{min}: min. concrete cover; meanCF: mean concrete cover; σCF: std concrete cover.

The modulus of elasticity of the concrete basements exhibit quite variable values (Table 4). This modulus is an important parameter for mortar reprofilation with protecting function of the concrete. In fact, a higher rigidity of the protecting mortar as compared to the underlying concrete would result in cracking of the previous material. In this concern, only the values ranging from 21263 to 24559 appear a little critical for the overlying with mortar (Table 4). Nevertheless, the modulus of elasticity of concrete are generally high and allow the application of most of the repair mortar types with lower modulus of elasticity.

Concrete basements			
ID	Sampling	Apparent density [kg/m³]	Modulus of elasticity [N/mm²]
1.1.1		2.43	24559
1.12		2.30	21263
4.1	Pile basament	2.25	40211
5.4		2.53	28048
6.1		2.42	36465
6.4		2.38	37931
7.1		2.40	41210
7.2		2.43	44092

Table 4: Modulus of elasticity and apparent density of the concrete basements.

The residual AAR expansion and susceptibility was measured on concrete specimens. The samples exhibit a mean value at 3 months of 0.211 ± 0.074 % and 0.215 ± 0.076 at 6 months caused by the AAR expansion (Table 5).

ID	Sampling zone	Δl_T [%]	Δl_{Idr} [%]	3 months		6 months	
				Δl_{TOT} [%]	Δl_{AAR} [%]	Δl_{TOT} [%]	Δl_{AAR} [%]
1.1.1				0.299	0.264	0.307	0.272
1.1.2				0.171	0.136	0.177	0.142
6.1	Pile basement	0.019	0.015	0.142	0.107	0.142	0.108
6.4				0.247	0.212	0.254	0.220
7.1				0.290	0.256	0.283	0.249
7.2				0.326	0.291	0.336	0.301
Mean value and std					0.211 ± 0.074		0.215 ± 0.076

Table 5: AAR expansion data collected by immersing the concrete specimens in a NaOH solution at 38°C. Δl_T[%]: deformation due to thermal excursion; Δl_{Idr}[%]: deformation due to water immersion; Δl_{TOT}[%]: specific deformation due to immersion in the NaOH solution; Δl_{AAR}[%]: real specific deformation due to AAR reaction.

The graphs indicate the trend during time of the expansion. Within one month, the specimens tested with accelerated expansion tests reached the peak expansion. After one month the expansion levelled off (Fig. 4 left-right).
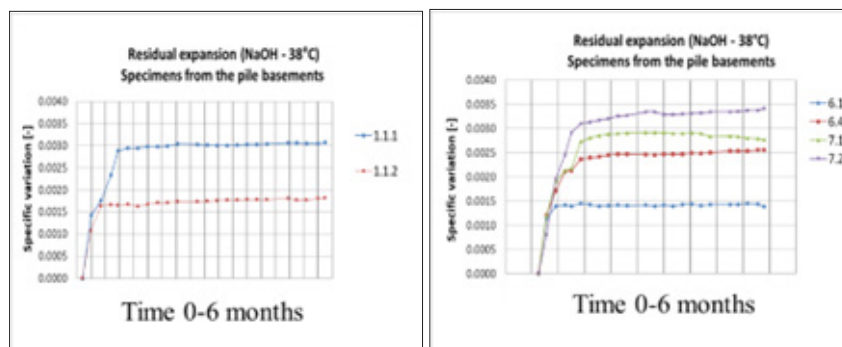
Figure 4: Expansion during time up to 6 months of the concrete specimens exposed to the solution. The measurements were done every 10 days.

Aggregates can be considered poorly reactive if the expansion is limited to $\Delta l_{AAR} \leq 0.05[\%]$ after 3 months and $\Delta l_{AAR} \leq 0.10[\%]$ after 6 months (Standard EN 8520-22, Concrete aggregates, part 22, Method to evaluate the potential alkali-silica reactivity of the aggregates, 2020). In this case, concrete specimens were tested, in order to estimate the potential susceptibility to AAR expansion. Because of the rapid and residual expansion showed by the samples, the concrete is still to be considered potentially reactive to alkali-silica reaction. This in spite of the already clear presence of such phenomena and the wide openings of the cracks and high damage extent. In particular, the relative high humidity present in altitude may continue to trigger the alkali-silica reaction on a mid-term basis.

Conclusions

The alkali-silica reaction within the investigated concrete structures may significantly vary depending on the lithology, the environmental conditions and the reactivity of the stone aggregates. Local expansive cracks and material detachments are often seen. The humidity, the aggregates and the reactive alkalis interact on a long-term basis over 50 years and largely control the extension of the degradation. Repair mortar applied on concrete may act as a barrier against the reaction, but it is not be able to completely mitigate the AAR effect. In fact, the water and the high humidity present in altitude is difficult to lower even with a physical barrier. Furthermore, a water sealant organic epoxy coating may not be adequate in extreme variable temperature conditions, such as in altitude. In addition, internal humidity may diffuse to the surface causing bubbles, rupture and detachment of the coating, also on a large scale.

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