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AAR IN UNDERGROUND STRUCTURES OF SWITZERLAND - A SURVEY

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ABSTRACT:

Currently the work for two new railroad tunnels through the Swiss Alps with a length of 35 and 57 km respectively is in progress. Prepared aggregates quarried from the tunnels are reused for the concrete. About 50% of these aggregates are classified as reactive in regard to AAR according to the AFNOR P 18-588 microbar test. In order to collect information about AAR in concrete exposed to underground conditions, eight existing tunnels are investigated in this study. The concrete and shotcrete of the 16 coring site studied is between 19 to 44 years old. Although signs for AAR are present in the microstructure of the majority of the samples, the visual inspection of the tunnels and the physical properties of the concrete and shotcrete indicate no substantial damage. The aggregates of seven coring sites are classified as reactive, but they obviously do not reach their reaction potential. One of the reasons might be the minor climatic fluctuations in the tunnels. The results of this study indicate that reactive aggregates might be used for concrete in tunnels without causing damage due to AAR.

Key words: Alkali-aggregate reaction, Underground structures, Damages

1 INTRODUCTION

Damages due to alkali-aggregate-reaction in concrete have been observed worldwide [1,2]. A variety of structures such as dams, bridges, walls and pavements are affected. In Switzerland the first case of AAR was published in 1995 [3]. In recent years several cases of AAR have been reported [4,5].

Currently the work for two new railway tunnels through the Swiss Alps with a length of 35 and 57 km respectively is in progress. After being prepared rock quarried from the tunnels is reused as aggregate for concrete applied in the tunnels. About 50% of these aggregates have shown a reaction potential for AAR in the microbar test [6]. The temperature in the tunnels will reach up to 40 °C due to their great depth. The relative humidity in the tunnels is expected to be between 40 and 80 %. These conditions would enable an AAR to take place if the aggregate used is reactive and a sufficient amount of alkali ions in the pore solution of the concrete is present. A service life of 100 years without maintenance work is required. Because the durability of the two structures is of vital importance for the European railroad traffic, measures have to be taken to prevent damages caused by AAR [7].

In this study the concrete and shotcrete of eight existing tunnels are investigated in order to verify the existence of AAR in Swiss underground structures and to characterize the degree of damage present.

2 METHODS

The age of the tunnels investigated ranges from 19 to 82 years. They are between 0.81 and 15.4 km long. The various tunnels are used for railroads, roads or for maintenance work in hydroelectric plants. Because AAR was not known in Switzerland at the time of their construction no measures to prevent AAR were taken. First, a visual inspection of a part of the tunnels was conducted over a total length of 28.2 km. During these inspections indications for AAR such as typical crack patterns, pop outs and excessive deposits on the surface were recorded. Data about the temperature and the humidity were collected from the local authorities or were measured during the inspections and the coring. The cores were taken at 16 different sites where the concrete or shotcrete showed indications for AAR. No samples were taken within the portals. The age of the samples

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Table 1 Materials and properties studied (conc: concrete; shcr: shotcrete)

Tunnel	Age	Material	Mechanical properties	Petrography	Microstructure	Microbar test
A1	22	conc	+	+	+	+
A2	22	conc	+	+	+	+
A3	22	shcr	+		+	
B1	21	shcr	+	+	+	
C1	21	conc	+	+	+	+
C2	21	shcr	+	+	+	+
C3	21	shcr	+		+	
D1	21	conc	+	+	+	+
D2	21	shcr	+		+	
E1	21	conc	+		+	
F1	19	shcr	+	+	+	+
F2	19	shcr	+	+	+	+
F3	19	shcr	+	+	+	
G1	22-24	shcr	+	+	+	+
G2	22-24	conc	+	+	+	+
H1	42-44	conc	+	+	+	+

taken for laboratory tests ranges from 19 to 44 years.

Flexural strength, compressive strength and porosity were measured according to SIA 162/1 [8]. In the porosity test total porosity n and the volume of capillary pores w_{cp} were determined. Cores were crushed and the aggregates separated to study the petrography of the aggregates using a magnifier and a microscope on the grain size 1-4 mm. Additionally the potential reactivity was measured with the microbar test [6]. This test method is similar to other accelerated mortar bar tests like the ASTM C 1260 [9] and the NBRI method. According to their expansion the test samples are classified as not reactive, reactive or strongly reactive (NR: expansion ≤0.10%, R: expansion >0.10% - <0.20%, SR expansion ≥0.20). Four quarries used to produce the aggregate for the concrete of seven different coring sites were located. The potential reactivity and the petrography of the recent production (grain size 4-8 mm) were studied. The microstructure of the concrete was examined with thin sections (45 x 70 mm^2) impregnated with fluorescent dyed epoxy resin using a polarization microscope. Additionally three fractured and uncoated samples of concrete were investigated with an environmental scanning electron microscope (ESEM-FEG XL30). The operating conditions of the ESEM were between 15-20 kV and 0.5-1.5 Torr. Energy dispersive X-ray spectroscopy (EDX) was used to identify the chemical compositions of minerals. The samples used to study the microstructure were taken from a depth relative to the concrete's surface between 100 and 200 mm.

3 RESULTS

3.1 Visual inspection

In all tunnels indications for AAR are found. The concrete and shotcrete within the portals often shows a more frequent cracking than in the tunnels themselves (A1, E1, F1 G, H1).

3.2 Physical properties

The compressive strength of the concrete and the shotcrete varies between 32.2-76.9 MPa and 34.5-66.6 MPa respectively (Table 3). The values for flexural strength range from 4.2-7.1 for the concrete MPa and 4.5-6.7 MPa for the shotcrete. The measurements for the porosity show big differences as well with values for total porosity n between 12.9-18.4 and 19.8-26.5 percent by volume respectively.

The compressive strength shows a good correlation to the volume of capillary pores (Fig. 1):

$$f_c = 94.6 - 5.4 \cdot (w_s - w_{50}) \qquad R^2 = 0.80 \qquad \text{(Eq. 1)}$$

The average compressive strength of the shotcrete is slightly higher at an identical volume of capillary pores compared to the concrete.

The compressive (f_c) and flexural strength (f_f) correlate relatively well (Fig. 2):

$$f_f = 0.104 \cdot f_c \qquad R^2 = 0.49 \qquad \text{(Eq. 2)}$$

Table 2 Conditions at the coring sites (shcr: shotcrete; conc: concrete)

Tunnel	Humidity [%]	Temperature [°C]	Indications for AAR on surface	Deposits on surface	Ground water
A	35	19 to 21	lateral cracks	some calcite on shcr	no
B C D	60 - 75	15 to 21	shcr: some cracks, and pop outs, isolated leaching	some calcite on conc	few zones
E	30 - 95	-20 to 20	AAR cracks within portal (conc)	no	no
F	85 - 95	17 to 19	shcr: leaching zones with aggressive water	seldom calcite	few zones
G	70 - 80	15	AAR cracks within portal (shcr)	some calcite in shcr	few zones
H	80	12	AAR cracks in portal zone (conc)	some calcite in shcr	few zones

Table 3 Physical properties and porosity

Tunnel	Material	Compressive strength [MPa]	Flexural strength [MPa]	Total porosity n [vol-%]	Volume of capillary pores w_{cp} [vol-%]
A1	conc	59.9 ± 5.0	6.3 ± 0.2	15.1	6.0
A2	conc	32.2 ± 1.9	4.5 ± 0.8	16.4	10.6
A3	shcr	35.8 ± 3.5	4.5 ± 0.1	23.2	10.6
B1	shcr	48.3 ± 4.5	5.5 ± 0.6	24.7	9.3
C1	conc	47.4 ± 3.7	5.1 ± 0.4	18.4	8.8
C2	shcr	40.7 ± 11.7	5.1 ± 0.2	21.3	9.1
C3	shcr	54.8 ± 4.7	5.6 ± 0.5	21.7	8.6
D1	conc	76.9 ± 6.8	7.1 ± 0.7	13.2	3.8
D2	shcr	64.6 ± 8.2	6.0 ± 0.7	21.4	6.9
E1	conc	53.4 ± 11.6	6.4 ± 0.5	13.7	6.9
F1	shcr	52.2 ± 4.5	5.4 ± 0.8	20.2	7.2
F2	shcr	66.6 ± 5.6	6.7 ± 0.4	19.8	7.3
F3	shcr	34.5 ± 2.6	-	26.5	12.0
G1	shcr	49.8 ± 10.2	4.8 ± 0.3	20.8	7.5
G2	conc	40.3 ± 1.3	4.2 ± 0.8	17.2	8.8
H1	conc	57.4 ± 12.3	5.8 ± 0.7	12.9	5.8

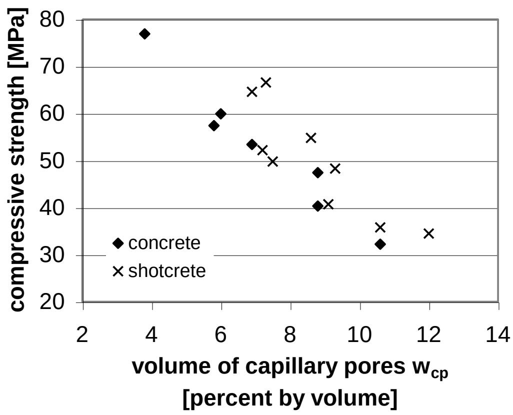

Fig. 1: Compressive strength versus the volume of capillary pores w_{cp}.

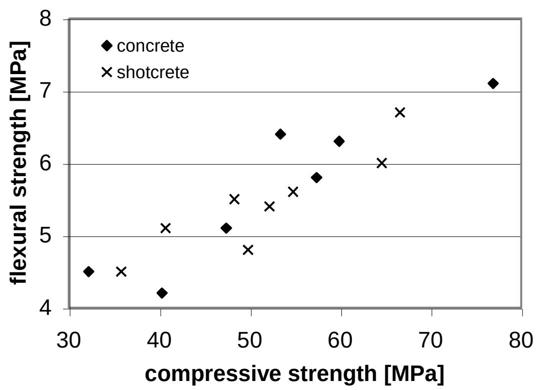

Fig. 2: Flexural strength versus compressive strength.

Table 4 Petrography of the extracted aggregates in percent by mass

Tunnel	Granite [%]	Gneiss, schist [%]	Lime-stone [%]	Siliceous limestone [%]	Sand-stone [%]	Slates [%]	Green-stones [%]	Rock fragments [%]
A1/A2	41	23	-	-	6	3	5	22
B1	10	18	13	7	-	1	4	47
C1	10	22	8	5	-	1	3	51
C2	30	36	-	-	3	-	10	21
D1	21	34	6	4	5	-	1	34
F1	22	24	-	-	-	12	-	42
F2	34	24	-	-	-	14	-	28
F3	14	21	-	-	3	-	3	59
G1	16	-	18	17	18	-	3	28
G2	24	28	-	-	2	-	2	44
H1	-	44	3	-	-	6	6	41

3.3 Petrographic examination

Igneous rocks are a major component of all aggregates except G1 (Table 4). All the igneous rocks are deformed and altered in various degree and can be divided into granite, gneiss and schist. The major sedimentary rock types are sandstone, limestone, siliceous limestone and slate. Because the petrography had to be carried out on the grain size 1-4 mm, it was not possible to relate all fragments to a rock type. But the mineralogy of the fragments represents the one of the identified rock types of each aggregate.

3.4 Microbar test and microscopy

The average expansion of the nine aggregates classified as NR is 0.058% with 0.040 (G1) being the lowest value (Table 5). Six are classified as R and one as SR.

On the surface of all cores aggregates with reactions rims at the edge were recognizable. The number of aggregates affected varies strongly depending on the coring site.

Deformed quartz grains with undulary extinction and diffuse grain boundaries were present in the thin sections of all samples studied. Feldspars altered to sericite are common as well. Biotite, muscovite and chlorite occur in all samples. There are gel deposits in air voids and cracks of six different samples (Table 5). All these samples show a distinct crack pattern including radial cracks running from the aggregate into the hardened paste (Table 5). Additionally five other samples without gel deposits show this crack pattern. The cracks occur in aggregates with a diameter greater about 4 millimetres. The reactive aggregates identified are schist, gneiss and granite (Table 5). In two cases cement with blast furnace slag was used (F2, D2). Otherwise ordinary Portland cement was applied.

In all three samples investigated with the ESEM quartz with dissolution phenomena was observed. Additionally there was feldspar and biotite (Fig. 3) with dissolution phenomena in the samples C2 and C3 (Table 5). In all samples there were deposits of gel in cracks and voids. The main component of the gels was always silicon and calcium with minor amounts of potassium and sodium. On the surface of some quartz grains the formation of card house structured gel was observed (Fig. 4). This type of gel was observed as well on the surface of quartz located at the edge of aggregates in all three samples studied.

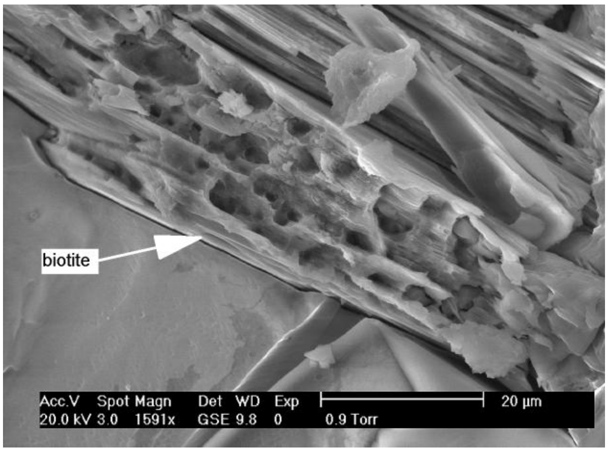

Fig. 3: Biotite with dissolution phenomena. Sample C2.

Table 5 Indications in the microstructure for AAR and results from the microbar test. The terms in brackets in the column on the right show the classification for the potential reactivity determined in samples with identical petrography.

Tunnel, quarry	Reaction rims [%]	Formation of gel	Radial cracks	Reactive rocks	Reactive minerals	Microbar expansion [%]	Mikrobar classifica-tion
A1	25-50	no	no	none	-	0.074	NR
A2	0-25	no	few	gneiss	-	0.142	R
A3	50-75	yes	few	gneiss, schist	-	-	(NR/R: A1, A2)
B1	0-25	no	no	none	-	-	-
C1	0-25	no	few	gneiss	-	0.070	NR
C2	25-50	yes	many	gneiss, schist	quartz, feldspar, biotite	0.068	NR
C3	50-75	yes	many	gneiss, schist	quartz, feldspar, biotite	-	(NR: C1, C2)
D1	0-25	no	no	none	-	0.154	R
D2	0-25	yes	few-many	sandstone gneiss, schist	-	-	(R: D1)
E1	0-25	yes	few-many	gneiss	-	-	(R: D1)
F1	0-25	no	few	gneiss, granite	-	0.052	NR
F2	0-25	no	few	gneiss, granite	-	0.056	NR
F3	25-50	no	no	none	-	-	(NR: F1, F2)
G1	25-50	no	few-many	gneiss, schist	-	0.040	NR
G2	50-75	yes	few-many	gneiss	quartz	0.052	NR
H1	0-25	no	no	none	-	0.130	R
D1 and G1	-	-	-	-	-	0.272	SR
F1 and F2	-	-	-	-	-	0.065	NR
G2 and F3	-	-	-	-	-	0.046	NR
H1	-	-	-	-	-	0.135	R

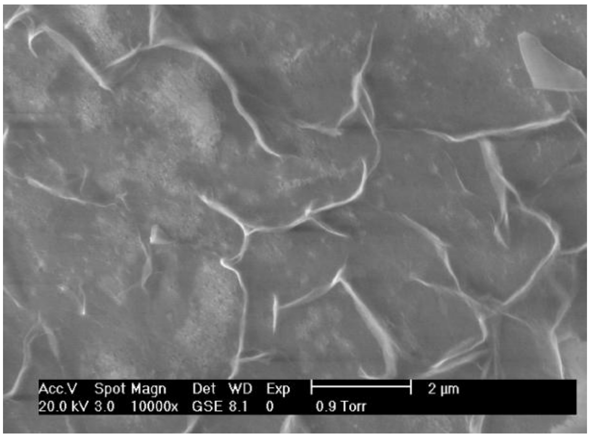

Fig. 4: Formation of gel on surface of quartz. Sample C2.

4 DISCUSSION

At a relative humidity above 70-80 % the expansion due to AAR is significantly increased [10,11]. Although the relative humidity in the majority of the tunnels is usually below 80 % the infiltration of groundwater leads to high moisture contents in the concrete and shotcrete locally. Furthermore, already a short period of high humidity can lead to damages due to AAR [11].

There is no data available about the mix designs used for the concrete and shotcrete. Based on the results of the porosity and the compressive strength the cement content of the shotcrete can be estimated at 350 kg/m^3 for tunnel F up to 400 kg/m^3 for tunnel H. The estimation for the cement content of the concrete is between 300 and 360 kg/m^3. The Na_2O-equivalent of the Portland cements is supposed to be between 0.9 up to 1.0 % by mass concluding from the values of recent Swiss cement production.

The results for porosity and compressive strength show that the concrete and the shotcrete in the different tunnels were made with a wide variety of cement contents and w/b-ratios. The good correlation between compressive strength and the volume of capillary pores indicates that no significant damage is caused by the AAR. In case of a substantial damage low values for compressive strength could be expected at a given volume of capillary pores. In general the decrease in the flexural strength due to cracks is higher than the decrease of the compressive strength. The values for compressive and flexural strength correlate well indicating no substantial damage as well.

Although higher cement contents are used in the shotcrete compared to the concrete, there are no differences between the two in regard to the degree of AAR. There is no correlation between the amount of aggregates with a dark rim and the occurrence of gel deposits and cracks.

The dark rims of the aggregates do not necessarily indicate AAR. Because the aggregate is quarried from alluvial deposits some of these reaction rims might be caused by weathering. However, in the two shotcrete and the concrete sample investigated with the ESEM the precipitation of gel at the edge of aggregates with dark rims could be observed.

The observed crack pattern with radial cracks running from the aggregate into the paste are a typical phenomenon caused by the expansion of aggregates [12]. Therefore they can be used as an indication for the presence of AAR.

The precipitation of gel in voids and cracks clearly indicates that a dissolution and subsequent precipitation of SiO_2 takes place. The most frequently etched mineral in the three samples studied with the ESEM is quartz. However, dissolution phenomena on feldspar and biotite indicate that these minerals additionally provide a contribution of alkali ions to the pore solution. It has been shown that milled feldspars release alkali ions when treated with alkaline solutions [13]. Apart from feldspar biotite and chlorite can be etched when stored in a NaOH or $Ca(OH)_2$ solution [14]. Furthermore, various feldspars are able to influence the composition of the pore solution in mortars [15].

The test results for the potential reactivity of the aggregates extracted from the concrete do not necessarily represent its original reaction potential because some reaction might already have taken place in the concrete. But in general there is no big difference between the test results obtained with aggregates extracted from cores and aggregates directly from the quarry. An exception is sample G1. The aggregate extracted from the shotcrete is classified as NR, while the sample from the quarry is classified as SR although the petrographic examination showed a similar composition of the two. No explanation for this contradiction is found.

There is a certain correlation between the different indicators for AAR in the microstructure of the concrete. The formation of gel deposits and the occurrence of radial crack patterns are observed in six samples. But five samples with cracks do not show gel deposits. Obviously the expansion of aggregates is not always accompanied by the formation of gel deposits in air voids and cracks. The reason for this observation might be that AAR does not take place homogeneously in the concrete and therefore there are differences in the spatial distribution of the indicators. Another possibility for the difference is the concentration and ratio of calcium, sodium and potassium in the pore solution favouring either dissolution with subsequent precipitation or expansion [16,17,18].

Even the samples with aggregates classified as NR show signs for AAR in the microstructure. Their mean expansion of 0.058% in the microbar test indicates a certain reactivity explaining this observation. But none of the aggregates classified as reactive causes a substantial damage of the concrete structures. One .even does not exhibit indications for AAR. Obviously the aggregates do not display their reaction potential although the climatic conditions are appropriate. One of the reasons might be the minor climate fluctuations in the underground structures. There are seasonal variations in temperature and humidity but no daily changes. It stands out that the frequency of cracks is increased within the portals of several tunnels. There the concrete is subjected to much greater variations of humidity and temperature that may accelerate AAR [19]. On the other hand the meaningfulness of accelerated test methods and their correlation to the expansion of concrete in the field are still not documented sufficiently [20,21].

Due to the results of this study reactive aggregates are currently used for concrete and shotcrete in the two new tunnels. The measures taken to prevent AAR are the use of cement with puzzolanic admixtures and the installation of liners to prevent the contact between concrete and ground water [7].

5 CONCLUSIONS

AAR takes place in underground structures of an age between 19 and 44 years.

The field observations and the physical properties of the samples show that no substantial damage occurs although reactive aggregates and indication for AAR are present.

The minor climatic fluctuations in the underground structures may not support the development of AAR.

The influence of temperatures up to 40°C on the development of AAR in underground conditions is not known.

There is no direct correlation between the amount of gel formed and the degree of cracking in concrete and concrete with AAR.

The reliability of the microbar test in predicting AAR can not be assessed because no structures with reactive aggregates showed substantial damage.

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