ALKALI-AGGREGATE REACTION IN NORWAY AND SWITZERLAND. SURVEY INVESTIGATIONS AND STRUCTURAL DAMAGE

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Abstract

It is hypothesed that in case the parameters climate, aggregates and concretes are "similar" the behaviour of Alkali-Aggregate Reaction is "similar" too. This hypothesis has been verified on the basis of a large number of field survey data from Norway and Switzerland. Statistics of cracks supposed to be caused by AAR on more than 1100 structures are presented. The crack width increases significantly by time and yearly growth rate for most structures is less than 0.1 mm/year in both countries. Many of the aggregate types documented as reactive in concrete structures in Norway and Switzerland are of same origin and all slow/late expanding type which require high alkali cement to be alkali reactive in concrete. An incubation period of 10-20 years before cracks are visible on the concrete structures occurs in both countries. It is concluded that the behaviour of AAR is in many ways similar in Norway and Switzerland.

Keywords: Survey investigation, concrete structure, crack width measurement, crack growth, alkali silica reaction

1 AIMS

To show that the behaviour of AAR is "similar" in concrete structures in case the parameters: aggregates (reactive silica), climate (water and temperature) and cement (sodium and potassium content) are "similar". This hypothesis should be validated by the comparison of the results from Swiss and Norwegian survey investigations. Hereby, experiences, test methods and preventive - remedial measures should be transferable and practicable in both countries and other countries with similar geology, climate and use of same cement types. Another aim is to show that survey investigation of a high number of structures and following statistical analysis is an important tool for obtaining an overview of AAR on a national and regional basis.

2 INTRODUCTION

2.1 History

Norway: First documented case of AAR in Norway was in 1977 [1] but AAR was first accepted as a real concrete problem in the early 1990s. National research projects have given the necessary scientific and technical knowledge to deal with this problem and for recommendations of preventive and remedial measures. The first research project 1990-1993 "Alkali Aggregate Reaction in Southern Norway" deals with survey investigations of structures in Southern Norway, micro structural examination of concrete (diagnosis), alkali reactive aggregates (negative list), laboratory test methods (establishment of test methods) and rehabilitation (Hunderfossen dam) [2, 3, 4]. The project included Viggo Jensen's doctoral thesis [5] and was the basis for the first Norwegian recommendations on AAR [6, 7, 8]. The second research project 1993-1996 "Alkali Aggregate Reaction in Northern Norway" deals with survey investigations of structures in Northern Norway, micro structural analyses, assessment of the petrographic method and a new in situ measurement system for measurements of relative humidity and expansions [9, 10, 11]. By this project the "mapping" of AAR in Norway was completed. Two succeeding projects 1997-1999 "Normin 2000" [12] and 2000-2003 "Field examination" [13] have provided the basis for revision of the Norwegian recommendation on AAR "NB 21 2004" [14, 15]. The last research project examined about 160 structures with age 20-45 years according to the Norwegian system (see later) but the results have not been available to the authors. A review of the history of ASR in Norway is given in [16].

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Switzerland: A review of the history of ASR is given in [17].Problems with AAR became significant only within the last 10 years when numerous structures built in the years from 1960 to 1980 started to show signs of AAR deterioration. During this period the largest portion of the Swiss roads networks has been constructed. The evaluation and significance of these damages was difficult, since the various regions of Switzerland are affected very differently, and experiences and appreciation vary from county to county (canton). Moreover, in Switzerland the AAR damages develop very slowly over several decades.

The objective of the Swiss research project (2001-2006) was to obtain an overview of the Swiss situation of concrete structures damaged by AAR [18]. The results of the research project have provided the necessary basis for the practical evaluation of the significance of these damages for the attention of public and private owners, planning civil engineers, national standard committees etc.

The urgency of the AAR situation has been analyzed by means of the geographical distribution, frequency, damage extent and type of affected structures. Corresponding measures for new constructions and for damaged structures have been proposed to public owners. Swiss recommendations on AAR are in process.

2.2 Geology, climate and cements

The geology in Norway and Switzerland is dominated by so called Alpino-type tectonics which are major over thrusting of huge plates (nappes) with complex rock compositions [19]. In Norway this occurred in the Caledonian Orogeny (Silurian-Devonian period about 435 – 395 million years ago) and Switzerland in the Alpine Orogony in late Tertiary period to present time. The natural aggregates in Norway and Switzerland are generally taken from glacio-fluvial deposits from the latest glacial period. Recent lake and river deposits are also exploited in Switzerland. In the last decades an increasing amount of concrete aggregates are manufactured from crushed rock in both countries. The climatic conditions in Norway and Switzerland are dominated by wide temperature ranges and high and varying humidity. Freeze-thaw cycles belong to the usual exposure, requiring high concrete qualities. The potentially alkali reactive aggregates in Norway and Switzerland are of the slow late expanding type which require cements with high alkali content to be reactive. Cements with high alkali content have been used during decades both in Norway and Switzerland. Table 1 shows parameters important for AAR in Norway and Switzerland

2.3 Age of affected structures

In both countries investigated structures are dominated by examples with a construction age around 20-60 years but older and younger structures have also been investigated. Figure 1 shows the age distribution of structures (see section 3) and cement production/consumption relative to years in Norway and Switzerland. Left figure shows all investigated structures with and without signs of AAR in Norway, and right figure Swiss structures with AAR damage only. Note that the age distribution of structures more or less follows the production / consumption of cement in both countries. The close relationships to the cement production / consumption suggest that investigated structures in Norway and Switzerland are representatively selected. The Swiss results also indicate the existence of an incubation period on 10-20 years. The risk for AAR still is possible for new structures in case preventive measures are not applied in Switzerland.

3 FIELD INVESTIGATIONS

3.1 Survey investigations

Both in Norway and Switzerland survey investigation was important to get an overview of the AAR problem. It was important to use a field investigation system which is "objective" and where subjective assessments are limited. Furthermore, the system had to be efficient, fast and reliable. Fast because the statistical reliability is increased by a high number of investigated structures. Table 2 gives an overview of the most important data of the Norwegian and Swiss field investigations.

The field investigation system used in both countries was developed in Norway and hereafter called the "Norwegian system" [5, 20]. The most important measure is measurement of crack width caused by AAR in all structural elements; as well as an estimate of the extent of cracks (a subjective measure). Survey investigations according to the Norwegian field investigation system were carried out in Norway 1990-1996 and Switzerland 2002-2006. In Norway 689 structures randomly distributed in the whole Norway were investigated and the data processed into a database and classified according to the Norwegian classification system. In Switzerland 450 structures were investigated in a similar way.

The field investigations only indicate that AAR might have caused the damages in structures. Micro structural analysis always should be carried out to document the causes of the damage as done

in numerous structures in Norway and Switzerland (15-20%). Experiences show that the interpretation of the typical damage patterns (map cracking) is usually correct.

The large number of damaged retaining walls in Switzerland is surprising. For instance it is not clear, if this depends on the relative high frequency of the retaining walls at all or if walls represent a particularly risky exposure situation.

3.2 Geographical distribution of affected structures

Figure 2 left shows the geographical distribution of investigated structures in Norway. The field investigations in Norway revealed that 68% of investigated structures have varying signs of AAR, 17% with minor signs of AAR and 49 % with major signs of AAR (2% were investigated but not classified). All structures have been classified according to a classification system based on crack width and distribution in structural elements. Black points correspond to investigated structures and red points to structures where AAR in addition has been documented by micro structural analysis [5, 20]. Reacted aggregates in concrete structures have been "correlated" with reference bedrock samples and thereby given the basis for a bedrock map showing potentially alkali reactive aggregates. It has been shown that structures located within alkali reactive bedrock areas are more damaged relative to structures located outside such areas.

Figure 2 right shows the geographical distribution of 450 structures with signs of AAR in Switzerland. One point represents at least 1 to several structures on the same place. The alpine and prealpine region is delimited by the two lines. In Switzerland 80-90% of investigated structures showed minor to strong signs of AAR and a slow development of the damage and 10-20% strong and very strong signs of AAR and a fast development of the damage. Evidence for AAR has been observed everywhere, according to the fact that reactive aggregates are present in all parts of Switzerland [21]. Generally the alpine and prealpine region seems to be more concerned as other regions.

3.3 Crack width development

Figure 3 shows the distribution of maximum crack width in 572 structures in Norway (left) and in 108 structures in Switzerland (right) relative to the construction age. Results from other investigated structures are not included because of unknown or uncertain construction age. Note the similar distribution in both countries.

In Norway and Switzerland investigated structures are dominated with construction ages around 20-60 years. Because in Figure 3 the graphical distribution of the maximum crack width is influenced by an increased number of structures in some periods relative to periods with fewer structures (false peak height) the average maximum crack widths in 323 Norwegian structures have been calculated for each decade as shown in figure 4. Structures without cracks and without measurable cracks are not included in the calculations. Note that the average crack width increases significantly from 0.25 mm after 10 years to 2.25 mm until 60 years (2 mm during 50 years) and that the number of structures in each decade from 20-60 years is sufficient for statistical analysis. Figure 4, right figure shows an exponential curve and equation which gives the best fit of the average expansion from 10 to 60 years in Norway. The number of structures older than 60 years is not sufficient for statistical analysis (blue bars).

In Switzerland a similar pattern with significantly increased crack width by increased ages up to 60 years occurs as in Norway. However, the number of structures is not sufficient for statistical analysis and therefore not included here.

Figure 5 shows the frequency distribution of yearly crack openings in 323 structures in Norway and 103 structures in Switzerland. The estimation of the yearly crack opening is based on the ratio actual crack width / age of structure. This is only a simple linear approximation which does not take into account the unknown incubation time until cracks appear. For the Norwegian structures an incubation period of 15 years has been subtracted from the structural age. Structures younger than 15 years (negative value) are not included in the graph (left). For the Swiss structures, the values are not corrected by a theoretical incubation time. Note the similar distributions of crack opening in Norway and Switzerland.

Based on data from the field investigations it can be calculated that the median value of crack opening in Norwegian structures is 0.027mm/year. The Swiss median value corrected for an incubation period of 15 years is 0.030mm/year, which is very similar to the Norwegian median value. The median value of crack opening without correction is 0.013mm/year in Norway and 0.015mm/year in Switzerland. The correction of 15 years incubation time gives values about twice as high.

The variety of crack openings and crack widths are in good agreement with three point measurement of cracks by use of Demec gauge carried on several Norwegian structures [22, 23, 24, 25, 26, 27, 28]. Here most measurements vary between 0 and 0.1 mm. Variation or "change" in the crack openings over time has been observed in Elgester bridge in Trondheim, see figure 6 (left). Largest yearly crack opening has been measured on a dam structures during a period on 7 years to be 0.23 mm yearly, see figure 6 (right).

In both countries about 10-20% of the examined structures have a fast crack opening higher than 0.1 mm/year. However, most of the structures have a more moderate crack opening less than 0.1 mm yearly; which means that it takes more than 25 years to "grow" a crack width on 1 mm. In Norway 67% of structures have crack openings less than 0.05 mm/year, and 17 % higher than 0.1 mm/year. In Switzerland the crack opening are respectively about 70% 10% and here the crack opening is classified as "slow" respectively "rapid" (see table 3).

An analysis of the characteristics of Swiss structures with fast crack openings (exposure, concrete composition and quality, reinforcement etc.) gave no general explanation of the reason for this exceptional behaviour [18]. In some cases an additional effect of freeze-thaw might increase cracks significantly e.g. crack openings up to 0.6 mm/year might be influenced by freeze-thaw.

3.4 Crack index

In Switzerland the crack index after the French LCPC method [29] has been carried out on 103 structures and the expansion rate calculated. The results are presented in table 3 and figure 7. The crack development in a structural element is usually not homogeneous and influenced by different factors as discussed in [30]. The crack width measurements give not necessarily the real expansion rate of a structural element. Following [31, 32], the results are valid only if crack measurements are realised on the most exposed and cracked areas of the concrete surface. This kind of interpretation of the survey data represents only a general approach, giving some indications for a first rough evaluation of the significance of the damages. It cannot replace detailed measurements on a given structure.

The proposed limit values for the assessment of the AAR damage development in case of slow/late reactive aggregates are significantly lower than those for example proposed by the French recommendation of the LCPC [33], which have been defined as follows: 0.5mm/m/year expansion rate and 0.2mm/year crack opening limit values between slow and rapid AAR damage development.

The LCPC method has only been used on very few structures in Norway. Note that the crack opening (Norwegian method) and expansion rate (LCPC method) more or less give the same result.

4 TYPES OF DAMAGES

Both in Norway and Switzerland map cracking, longitudinal cracks and signs of volume expansion (movement of structural elements) occur in AAR damaged structures. The crack distribution in a structural element is usually not homogeneous and probably influenced by different factors including variations in humidity, temperature, geometry, reinforcement and variation in concrete composition. Sometimes cracking only occurs on one face of structural elements where other faces are without visible cracking. Due to reinforcement and often complex geometry of the structural elements longitudinal cracks in many cases are the only sign of AAR e.g. in beams. Both in Norway and Switzerland south oriented faces are more intensively cracked compared to other orientations.

Examination of cracks and crack widths is important for the assessment of the extent of AAR. Cracks will "grow" with different growth rates as demonstrated here. In an early stage, cracking affect mainly the outer concrete surface, while micro cracking due to AAR dominate deeper inside the concrete. In later stages of AAR surface cracks can penetrate deep into the concrete. Delaminating cracks (surface parallel cracks) also appear with progressive damage development [30, 34]. In later stages of the reaction the structural elements can be moved and coarser cracks dominate the concrete. Concrete fragments can fall off and occasionally the whole concrete structure can be parted into individual smaller "blocks" as seen in some few structures. Freeze-thaw cycles might increase the damage in more humid and horizontally located structural elements, e.g. railway sleepers, piers, foundations and pavements.

5 DISCUSSION AND SUMMARY

The results of the survey investigations allow some statements about damage and the damage evolution in case of slow/late expansive concretes. Regional or state-wide survey investigations are in most countries only possible to realise in form of national research projects. Survey investigations generate a practical basis for the evaluation of the need and urgency of preventive measures in the case of new constructions, as well for maintenance and repair of damaged structures. General features

of the damage development in concrete structures, first of all of the cracking, are a useful basis to the actually lacking but strongly necessary consideration by civil engineers. One issue of the survey investigations are to provide fundamental knowledge and documentation for the validation of laboratory test methods based on real structures.

The great number of examined structures in Norway and Switzerland should guarantee that the appraisals of data as presented in the paper are representative. The close relationship between investigated structures and cement production/consumption in both countries suggest that structures have been representatively selected. Within the research projects in Norway and Switzerland it was possible to examine and assess more than 1100 concrete structures. The interpretation of geographical data has to be carried out carefully, because other factors independent of AAR can strongly influence the geographical distribution, such as 1) the topography and the density of road network determining the regional frequency of civil engineer structures or 2) the age of the road network determining the type of utilised construction material (natural stone versus concrete). In Switzerland the geographical distribution of the damaged structures is strongly influenced by the road network and the density of structures. In Norway structures have been more or less randomly selected with this limitation that in more remote areas one had to select the structures that existed.

In both countries field investigations revealed that AAR is a widespread and common problem; 68 % of investigated structures in Norway showed varying signs of AAR. In Switzerland about 80-90 % of investigated structures showed minor to strong signs of AAR. It takes 10-20 years or more until first damage is visible by the unaided eye (incubation period). AAR damages on concrete structures develop slowly during decades but can grow very seriously over time. In Norway average crack width increases from 0.25 mm after 10-20 years to 2.25 mm after 50- 60 years. Moreover the growth rate is suggested to be exponential. About 70% of the Norwegian and Swiss structures with signs of AAR have crack openings less than 0.05mm/year classified as slow AAR and 10%-20% have crack openings larger than 0.1 mm classified as rapid AAR. The average crack opening (median) from all AAR damaged structures was 0.013 mm/year in Norway and 0.015 mm/year in Switzerland. Considering an incubation period on 15 years, the crack opening will be about twice as high. It is clear that these values give the order of magnitude of the damage development and could vary in each case. However, the magnitudes of crack openings and crack widths are in good agreement with three point Demec measurements in Norway.

The occurrence and distribution of cracks in a structural element is usually not homogeneous and probably influenced by different factors such as e.g. variations in humidity, temperature, reinforcement, geometry of the structural elements and others e.g. variation in alkali content. In Norway and Switzerland most structural element located south are more cracked than otherwise oriented elements probably due to higher temperatures by the sun.

Within an expected service live of at least 50 years (e.g. according to European standard EN 206-1) AAR caused by slow/late expansive aggregates causes significant damages in the concrete, which might influence the durability of the structure. Preventive and remedial measures are therefore justified in case of slow/late expansive aggregates and concrete structures located in humid environments.

Many structures in both countries are damaged in such a degree that repair measures are urgent. Beside prestigious and singular great civil engineers structures, many insignificant smaller structures exist, e.g. retaining walls, whose demolition, repair or eventually surface protection constitute a significant economic burden on the society.

Therefore an urgent need of fundamental research on several issues exists as: techniques for condition investigations and for assessment of existing AAR damaged structures, prognosis of the development of the AAR damages and techniques for protection and rehabilitation.

6 CONCLUSION

In Norway and Switzerland AAR is a common damage mechanism widespread in several parts of the countries due to slow/late expansive alkali reactive aggregates. In Norway most AAR damaged structures are located in areas dominated by alkali reactive bedrocks and in Switzerland in the alpine and pre-alpine regions.

Both countries have more or less similar conditions according to geology, climate and use of high alkali cements and behaviour of AAR. Survey investigations have given important knowledge on the extent, distribution and damages in both countries. Statistical analyses have revealed surprisingly similar distribution of crack width and crack growth in Norwegian and Swiss structures.

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Country	Norway	Switzerland		
Geology	Alpino-type tectonics, Precambrian and Permian	Alpino-type tectonics with quaternary glacio-fluvial and		
	rocks., glacio-fluvial natural aggregates	fluvial deposits in the sedimentary basins of the forelands		
Aggregates	Natural and crushed aggregates of gneiss, granite,	Natural and crushed aggregates of gneiss, granite, mylonite,		
	phyllite, mylonite-cataclasite, quartzite, sandstone,	phyllites, quartzites, carbonate sandstone, siliceous sandstones,		
	greywacke, siltstone, claystone, mafic and ultra mafic	greywacke, pure limestone and impure limestone, sandy or		
	rocks, felspatic rocks, <i>rhyolite</i> , pure limestone and	siliceous limestone. Usually the sand is crushed. About 85%		
	impure limestone, hornfels	of Swiss aggregates are considered as reactive (testing		
		after AFNOR NF P 18-594).		
Climate	Average temperature from minus 5 °C to plus 17	Average temperature from minus 5 °C to plus 18 °C,		
	^o C, average yearly precipitation from less than 400	average yearly precipitation from 300 mm to 1000mm		
	mm to more than 2400 mm rain and relative	rain and relative humidity from 65% to 90%. The		
	humidity from 65% to 90%. The winters are	winters are dominated by many freeze thaw cycles which		
	dominated by many freeze thaw cycles which might	might influence AAR damaged outdoor exposed		
	influence AAR damaged outdoor exposed	concrete.		
_	concrete.			
Cement type,	Ordinary Portland Cement with high Na2Oeq	Ordinary Portland cement, with high Na ₂ Oeq content		
alkali-content	content between 0.9-1.4%. Since the beginning of	between 1.0-1.8%. Low alkali cement, additions as slags,		
	2000th fly ash cement has been introduced as	microsilica or fly ashes have not been used. Since 1994		
	standard cement. Few structures with micro silica	introduction of other types of cement, most over OPC		
	additions.	with limestone filler		
Concrete quality	w/c-ratio: 0.40-0.60	w/c-ratio 0.45-0.55;		
(general)	Cement-content: 300-500 kg/m ³ ;	Cement-content 300-400kg/m ³ ;		
	Compressive strength (28d): 20-45 MPa	Compressive strength (28d) 25-45 MPa		
Italicised rock types are considered as potentially alkali reactive rock types				

TABLE 1: Important parameters for AAR in Norway and Switzerland.

Country	Nomyay	Switzerland			
Country	INOFway	Switzenand			
Number of	689 investigated structures	450 investigated structures			
structures					
Type of examined	Road bridges, concrete dams, hydro power plants,	Tunnels and galleries (17%), bridges (24%), walls			
structures	industrial and office buildings and railway sleepers (since	(45%), hydraulic structures (7%), various etc. (7%)			
	1994)				
General data from	Structure identification, coordinates, county /municipal	Structure identification, coordinates, road section,			
structures	no., road section, altitude, bedrock geology, age (if	altitude, age if available			
	available), structural element, type of structure,	structural element, type of structure (tunnel, wall etc.),			
	exposure/environment, deformation, other damages (e.g.	exposure, environment orientation,			
	frost), rehabilitation, surface protection.				
Data of damages	Crack distribution (percent) and crack width in all	Crack distribution, crack width, crack depth, crack			
-	structural elements, deformation (movement of structural	distance, water outflow throughout the cracks,			
	elements or reduction of joints) freeze-thaw	efflorescences			
	deterioration, reinforcement corrosion, efflorescence's,	general evaluation of damage extend,			
	photo documentation and classification of the structure.	other damages (e.g. freeze-thaw, corrosion), photo			
	P	documentation.			
Data from	Micro structural analyses*, cement content, alkali	Micro structural analyses*, cement content, alkali			
concrete cores	content, compression strength and porosity (some	content, loss of mechanical resistances (compressive			
(selected	structures), petrography of aggregates. Since 1995 in-situ	and tensile strength, E-modulus), freeze-thaw			
structures) and	measurement of relative humidity and expansion	resistance, chloride migration resistance, porosity,			
special	measurement of cracks in some structures.	petrography of aggregates			
investigations					
* Micro structural analysis is a visual method examining concrete cores, fluorescence impregnated polished halved cores and fluorescence					
impregnated thin sections by microscopic methods.					

TABLE 2: The most important data from the field investigations.

TABLE 3: Classification and assessment of cracks and damage evolution in Swiss structures.

Parameter: calculation	Unit	Assessment of AAR		Number of structures	
Crack Index:	[mm/m]	< 1	little damage	ca. 40-50%	
Cumulated crack width / length measure		≥ 1	moderate damage	ca. 40-50%	
profile		≥ 3	serious damage	ca. 10-20%	
Crack opening:	[mm/year]	< 0.05	slow AAR	ca. 70 %	
max crack width/structure age*		≥ 0.1	rapid AAR	ca. 10%	
Expansion rate:	[mm/m/year]	< 0.1	slow AAR	ca. 70%	
crack index / structure age*		≥ 0.2	rapid AAR	ca. 20%	
*: without correction of incubation time					



Figure 1: Left: Age distribution of all investigated structures with and without AAR damages and cement production relative to years in Norway. Right: Age distribution of investigated structures with AAR damages only and cement consumption relative to years in Switzerland.



Figure 2: Geographical distribution of structures with signs of AAR in Norway (left) and Switzerland (right). Red points correspond to more detailed investigated structures by micro structural analysis [5, 18, 20].



Figure 3: Distribution of maximum crack width relative to construction age in structures in Norway (left) and Switzerland.



Figure 4: Histogram of average maximum crack width versus construction age in decades (left) and en exponential curve and equation of best fit (right). Number of structures on top of bars.



Figure 5: Frequency % of yearly crack width opening in Norway (left) and Switzerland (right).



Figure 6: Increase of crack opening during 9 years measurements in Elgeseter bridge in Trondheim (left) and during 7 years on a dam structure in Southern Norway (right).



Figure 7: Calculated annual crack opening and expansion rates in function of the crack index of 103 structures (Switzerland).



Figure 8. Extensive cracking due to AAR and freeze-thaw in a dam pier from Norway (left) and from .Switzerland (right).