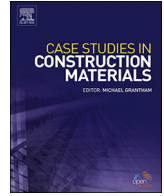




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Case study

Alkali-silica reaction in Southern-Finland's bridges

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ABSTRACT

In Central Europe and Scandinavia, alkali-aggregate reaction (AAR) typically occurs in massive concrete structures such as bridges and dams. Despite of having similar bedrock with Sweden, Finland has been considered as an AAR free country. The scope of this study was to find out the existence of alkali-silica reaction (ASR) in Finnish bridges. It was also studied how the age of the bridge as well as the aggregate type has affected the occurrence of ASR. The research material consists of 97 condition assessment reports from concrete bridges constructed between 1912 and 1999. The condition assessments were carried out during 2001–2014. All studied bridges are situated in southern or south-western Finland. Alkali-silica reaction was detected by petrographic analysis in 27 bridges, which is 27.8% of all studied bridges. Of the bridges built in the 1970s (38 bridges in the sample) 42.1% was affected by ASR. In the 1960s bridges (33 bridges in the sample) 17.6% was affected. The bridges showing ASR were 31–44 and 43–52 years old, respectively. Thus, there is a potential risk for having ASR damage in concrete bridges also in the Finnish construction and climate. The study shows, however, that the reaction has taken a considerable amount of time to be detected.

1. Introduction

The Finnish Road Administration has approximately 15100 road bridges to its upkeep in Finland [1]. In addition, about the same amount of similar bridges belong to the management of the cities and towns making together approximately 30 000 road bridges in Finland. Finnish bridges are generally quite young – over 95% has been built after 1950. The largest number of bridges were built in the 1960s and '70s. Over time, several different materials have been used to construct bridges including stone, wood, steel and concrete. The most prevalent building material, however, has been concrete. Reinforced and pre-stressed concrete bridges account for 68% of the bridge stock [1]. Moreover, the decks and substructures of steel bridges as well as the substructures of wooden bridges are also primarily of concrete making its share of the structures of the bridge stock even larger.

The bridge stock in Finland is under regular inspection system. Each bridge is inspected visually every five years. Based on this visual inspection systematic condition assessment will be ordered to the bridge before any repair activities. The inspection system provides up-to-date data on the condition of bridges, which allows determining the technical repair needs of various structural members of bridges in the future and the required financing. The inspection and assessment data on material and structural properties, durability and technical condition of the bridges is compiled in a nationally administrated Bridge Register along with road-specific road and traffic volume data, data on the structure and dimensions of bridges, and data on bridge fixtures and equipment. [2].

In Central Europe and Scandinavia, alkali-aggregate reaction (AAR) typically occurs in massive concrete structures like bridges and dams [3]. Despite of having similar bedrock with Sweden, Finland has been considered as an AAR free country due to its climate

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and the common aggregates used [4]. During the last few years, some dozens of ASR cases have been reported (Pyy et al., 2012; Lahdensivu & Aromaa 2015). The scope of this study was to find out existence of alkali-silica reaction (ASR) in Finnish bridges and to study how the age of the bridge as well as the aggregate type of concrete has affected the occurrence of ASR.

2. Alkali aggregate reactions

The alkali-aggregate reaction is an expansion reaction of the aggregate of concrete caused by the alkalinity of hydrated cement, which may disintegrate concrete. The existence of AAR was first discovered in USA in the 1940's, and it is generally divided into three types according to the reacting aggregate: alkali-silicate reaction, alkali-carbonate reaction and alkali-silica reaction [5]. All AARs require reactive aggregate, a sufficient amount of alkali ions in the hydrated cement, and a minimum relative humidity of concrete of 80% [3].

The alkali-silica reaction (ASR) is the most general form of AAR. For the alkali-silica reaction to take place, the pore water must contain dissolved sodium (Na_2O) and potassium (K_2O) alkalis, and the aggregate must contain minerals that have low resistance to alkalinity. The gel produced by the reaction absorbs much water from its surroundings, which causes its volume to grow leading to internal pressure within the pore system. As the building pressure exceeds the tensile strength of concrete, cracks form in the concrete structure allowing the relatively soft gel to extrude through them [6].

The alkali-silicate reaction is similar to ASR: the reaction mechanism is similar, but there are some differences in the physical and chemical form of gel and other reaction products. Disintegration process of concrete is remarkable slower than in ASR, so the reaction is usually called also slow or delayed alkali-silica reaction [7].

The alkali-carbonate reaction is effected by the alkalinity of some limestones and cement and produces a swelling clay-like substance. The gel that forms at high humidity swells about 4% by volume creating pressure within the pore system of the concrete. The cracking of concrete generates a cracking pattern and leads to a loss of bonds between the aggregate and the cement paste [6].

AAR generally means slow deterioration of concrete. Degradation rate is influenced by prevailing conditions as well as the quality of aggregate and cement. In the case of silicon-containing rocks, AAR develops sooner, in 2–5 years, whereas with slower reacting rocks like sandstone and limestone the reaction may take 10–20 years to develop. AAR has been reported to occur also with highly stable rocks such as granite, quartzite and sandstone [5]. With blended cements like blast furnace slag (BFS) and pulverised fuel ash (PFA), AAR is less common since fewer reacting alkalis are generally involved than with OPC [3].

A concrete structure suffering from AAR typically exhibits discolouration due to surface moisture, irregular pattern cracking, swelling and oozing of a gel-like reaction product from the cracks [6]. The damage from AAR resembles the cracking caused by frost attack and often coincides with it [3]. The most significant difference between AAR and frost damage is the pattern of cracking, which in the case of frost damage is the most intensive close to the outer surface and loses intensiveness with depth. AAR cracking begins deeper inside the concrete and produces a more regular cracking pattern across the entire concrete structure [8].

3. Research material

The research material consists of 97 condition assessment reports from concrete bridges completed between 1912 and 1999, see Fig. 1. The condition assessments were carried out during 2001–2014. All studied bridges are situated in southern or south-western Finland.

The basic aim of the condition assessment is to produce information about the factors affecting on the condition and the performance of the structure and consequently about the need and the options for repair for the owner of the building or structure. Damage to structures, its degree and extent, due to various degradation phenomena can be determined by a comprehensive systematic condition assessment [2,9].

In this study the most important information from the condition assessment reports was:

- the geographical location of the bridge
- age of the bridge when ASR was detected

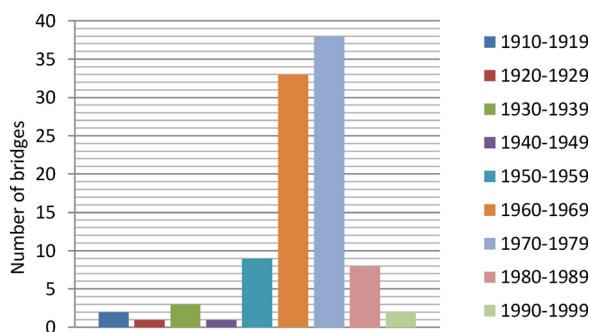


Fig. 1. Age distribution of the studied bridges.

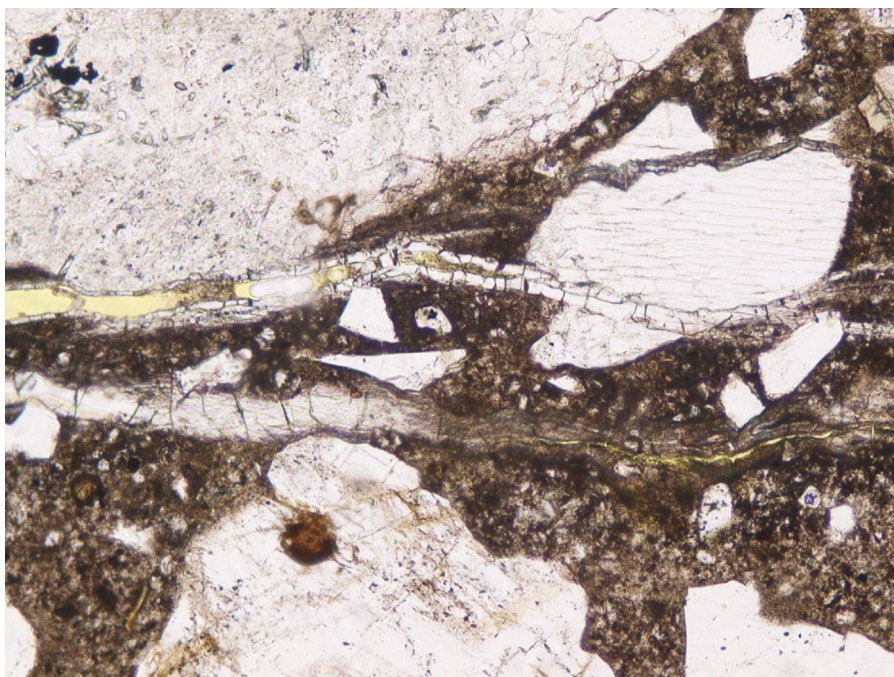


Fig. 2. Typical ASR finding in microscopy study. The visible area is approximately 1.1 mm × 1.4 mm (image by Arto Koskiahde).

- thin-section analyses (cement type, reactive aggregate, signs of ASR as cracking and reaction products), number of samples was 97
- tensile strength of concrete, number of samples was 33.

The research material was divided in two judging by the evidence on ASR damage to study the occurrence of ASR in Finland. The data was analysed for structure age and geographical distribution of the problem. Since the laboratory analyses (thin-section) can detect very early age reaction, this data was also used in studying the initiation time for ASR in Finnish (humid continental/subarctic) climate.

The prerequisites for ASR were studied as follows: i) the alkali content of cement based on Na_2O equivalent, ii) aggregate type based on the known reactivity, iii) moisture based on long term moisture monitoring data on bridge deck.

The effect on the structural integrity of ASR damage was studied from the concrete tensile strength test reports in the condition assessment data.

4. Results and discussion

4.1. Nature of ASR in this research material

Degradation of concrete was studied with thin-section analyses. This microscopy study expose all cracking of concrete as well as filling of pore structure and ASR gel. Typical ASR finding in microscopy study is shown in Fig. 2. Identifying of ASR from e.g. freeze-thaw damage or other cracking is crucial. Freeze-thaw damage is the most intensive close to the structures' outer surface and loses intensiveness with depth while AAR cracking begins deeper inside the concrete and produces a more regular cracking pattern across the entire concrete structure.

According to condition assessment reports ASR was detected only in thin-section analyses. No visual damage, gel oozing or swelling on the structure could be detected with a naked eye on the surface of the concrete structure or on core samples. This differs remarkably from the literature on typical marks of ASR. As a conclusion, it could be stated, that ASR detected from these concrete bridges was in early stage.

4.2. Occurrence of ASR

Alkali-silica reaction was found in 27 bridges, which is 27.8% of all studied bridges. The geographical location of bridges where ASR was found is shown in the map, see Fig. 3. Most of the cases of detected ASR are in Helsinki (6), Vantaa (5) and Turku (3) while other localities had only one or two cases. The found ASR cases are in the same area in southern and south-western Finland than those bridges where ASR wasn't detected.

The ASR was detected from 16 bridges which were built in 1970's. This is 59% of all found cases in this research material. The age of those bridges varied between 31 and 44 years, while average was 38.6 years. In all, there were 38 bridges made in 1970's and the



Fig. 3. Found ASR cases. All studied bridges are located in south and south-west Finland.

ASR share of those was 42.1%. Bridges made in 1960's was the second largest with the number of 33 bridges. ASR was detected six of them, which corresponds to 22% of found cases and 17.6% of all investigated bridges from 1960's, see Table 1. The age of 1960's bridges detected ASR varied between 43 and 52 years, average was 46 years.

Eight bridges were built in 1980's and ASR was detected on three of them, which is 11% of all ASR findings. It is 37.5% of all bridges made in 1980's, but the number of bridges is rather small for reliable statistical analysis. In the research material there is nine bridges from 1950's but no ASR was detected from those.

Table 1
Number of bridges and ASR cases in different decades.

Decade	Number of bridges	ASR detected		
		Number of bridges	Share from detected ASR cases [%]	Share from all bridges in the same decade [%]
1910	2	0	0	0
1920	1	0	0	0
1930	3	1	3.7	33.3
1940	1	0	0	0
1950	9	0	0	0
1960	33	6	22.2	18.2
1970	38	16	59.3	42.1
1980	8	3	11.1	37.5
1990	2	1	3.7	50.0
ALL	97	27	100	27.8

4.3. Initiation time for ASR

The bridge condition assessments were carried out to determine the maintenance and repair needs of the bridge, not for finding out especially ASR. However, it is still possible to estimate roughly the initiation period of ASR from the age of the bridge when ASR was detected.

According to condition assessment reports ASR was detected only in thin-section analyses, no visual damage was detected. Initiation time for thin-section detectable ASR varied between 22 and 77 years in this study. Mean initiation time was 42 years while standard deviation was 7.5 years. The initiation time for ASR might be some years shorter, because this was random sampling and condition assessment was made for another purpose than looking for ASR. All in all, it may be stated that ASR has relatively long initiation time in Finnish concrete bridges compared to literature [5].

4.4. Cement type in ASR cases

Cement type was detected from thin-section analyses. The most common cement type in Finnish bridges has been Portland cement (OPC) with share of 77% of bridges in this study. The share of blended cements with blast furnace slag (BFS) was 8% and with pulverized fly ash (PFA) 5%. In nine per cent of the cases, cement type was unknown or it wasn't reported.

In the bridges where ASR was detected, the cement type was in 20 cases OPC. It must be noticed that in Finland blended cements are still mainly composed of Portland cement (over 50%) with minor addition of BFS and PFA. Obviously, dissolved sodium (Na₂O) and potassium (K₂O) alkalis originates from Portland cement.

Concrete grade in superstructures used to be C20/25 or C25/30 until 1970's. Since the beginning of 1980's concrete grade has been at least C30/37. According to Finnish concrete codes the cement content in concrete has been usually 300 kg/m³ at least.

The alkali content of cement is a key property in the development of ASR and it should be determined for estimating the possibility of the reaction. Alkalinity of Portland clinker consist of sodium and potassium. Alkali content of cement can be determined as a Na₂O equivalent:

$$Na_2O_{EQ} = (Na_2O\% + 0,658 K_2O\%) \tag{1}$$

According to some European standards, Na₂O_{EQ} should be less than 0.60% [10–12] to avoid ASR. Na₂O equivalent in the most used Finnish cement types varies between 0.80% and 1.35%. The alkali content is therefore considered sufficient for the development of ASR.

4.5. Reactive aggregate

Reactive aggregate was detected from thin-section analyses. Two most common reactive aggregate was granitic rocks (26%) and quartzite (24%). In 32% of cases, reactive aggregate was not recognised or reported in petrographic analysis, see Fig. 4.

All those reported reactive aggregates can be found typically in Finnish bedrock and natural rock material. However, those aggregates have been rated as relatively stable aggregates in literature [4,6], which may on its part explain why the initiation of ASR has taken a considerably long period of time of about 40 years.

4.6. Moisture of concrete

Moisture content on concrete structure was not measured from bridges where condition assessments were carried out. However, Finnish Road Administration has published a survey, where long term (2.5 years) relative humidity and temperature measurements were carried out in two concrete bridges' decks. The sensors were installed 20 mm under water proofing (1), 500 mm from the top of the deck (2) and 20 mm up from the soffit of the deck (3). Thickness of the concrete deck was 800 mm and 1200 mm [13]. One of the sensors was installed in edge beam (4), see Fig. 5.

Under the waterproofing relative humidity varied from 75% to 98%, and in the middle of the deck as well as in edge beam from

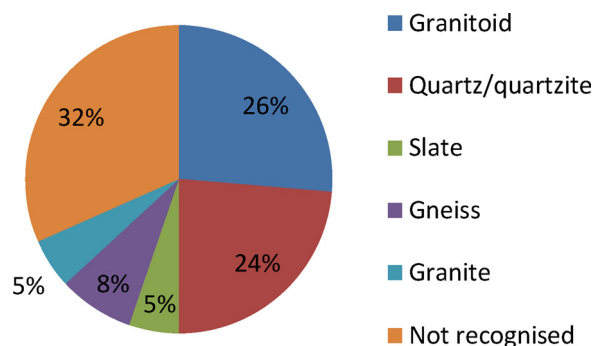


Fig. 4. Distribution of reactive aggregates (n = 38).



Fig. 5. Schematic location of sensors in the bridge deck [13].

86% to 100%. Despite of the waterproof or just because of it, relative humidity of concrete seems to stay almost constantly (approx. 95% of the time) over 85% RH. In the soffit of the deck, concrete can also dry. Relative humidity varied between 63% and 85%, while the average was 73%. At the same time, the temperature of the concrete structure varied between $-12\text{ }^{\circ}\text{C}$ and $+30\text{ }^{\circ}\text{C}$. Temperature of concrete follows air temperature in all measurement points in bridge slab.

4.7. ASR effect on tensile strength of concrete

Weathering of concrete caused by freeze-thaw damage, ASR or late ettringite etc. is considered to have adverse effects mainly via the loss of tensile strength of concrete. Totally 33 reports on tensile strength tests from the ASR affected structures were included in the research material. Tensile strength of concrete varied between 0.27 MPa and 3.50 MPa. According to national repair guideline for concrete [14], tensile strength of solid concrete should be at least 1.50 MPa, which was not fulfilled in a total of 16 samples out of 33. According to condition assessment reports, tensile strength of concrete was lower in 11 (33%) cases because of ASR and had probably some defects in five cases (15%), see Fig. 6.

In some cases, lowering of the concrete tensile strength due to ASR was evident even though the tensile strength was still in good level (2.08 MPa, 2.09 MPa, 2.10 MPa and 2.80 MPa).

Weathering of concrete will first affect the mechanical bond between either concrete and aggregate or concrete and reinforcement. Therefore, widespread and far advanced ASR will over time effect on the bearing capacity of the bridge. Moreover, the fracture mechanism will change from ductile to brittle, which is an undesirable phenomenon.

5. Conclusions

Condition assessment reports of concrete bridges made between 1912 and 1999 were subject to study to find severity of ASR in Finland. In all 27 ASR cases out of 97 were found in the research material (27.8%). It means that, opposed to what is believed, also in Finland there are problems with alkali-aggregate reactions in existing concrete bridges. Reported reactive aggregates were granitic rocks and quartzite, which can be found typically in Finnish bedrock and natural rock material. However, those aggregates have been rated as relatively stable aggregates in literature, which explains why initiation time of ASR has been taken considerably long period of time of about 40 years.

The relative humidity in concrete deck is most of the time of the year higher than 80%. Despite of relatively stable aggregates, this high relative humidity together with the high alkalinity due to Portland cement in concrete makes the probability of ASR in Finnish concrete bridges very high, knowing that the majority of the Finnish bridge stock has been built in 1960s and '70 s and is thereby reaching the age of 50–60 years.

The reasons for the relative slow reaction are most likely the relatively stable aggregates used and the cold climate. Further analysis on the material composition, construction and design practice as well as the cold climate conditions in Finland may provide knowledge on how to slow down the reaction also in other more aggressive climates.

ASR problem in Finnish concrete bridges is relatively small compared to corrosion of reinforcement or freeze-thaw damage of concrete. However, ASR possibility must be taken account in concrete slab under water proofing, where moisture content of the concrete is constantly high.

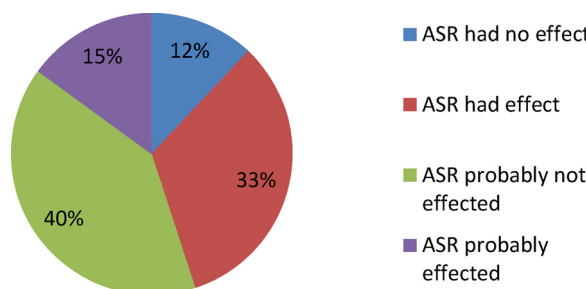


Fig. 6. Effect of ASR in tensile strength of concrete (n = 33).

Conflict to interest

Authors will ensure that there is no conflict to interest in this paper.

References

- [1] Bridges of Finnish Transport Agency. Structure, Service Level and Condition of Bridge Stock, Finnish Transport Agency, Statistics of the Finnish Transport Agency, Helsinki, 2015, p. 170 10/2015 (in Finnish).
- [2] Condition Assessment Manual for Bridges, Finnish Transport Agency, Guidelines of the Finnish Transport Agency, Helsinki, 2015, p. 142 26/2013 (in Finnish).
- [3] J. Punkki, V. Suominen, Alkali Aggregate Reaction in Norway –and in Finland? *Betoni* 2/1994, Suomen Betonitieto Oy, Helsinki, 2015, pp. 30–32 (in Finnish).
- [4] M.G. Richardson, *Fundamentals of Durable Reinforced Concrete*, Spon Press, London, 2002, p. 260.
- [5] O.E. GjØrv, *Durability Design of Concrete Structures in Severe Environments*, Taylor & Francis, 2009, p. 220.
- [6] A. Neville, *Properties of Concrete*, Longman Group, Essex, 1995, p. 844.
- [7] H. Pyy, E. Holt, M. Ferreira, *Prestudy on Alkali Aggregate Reaction and Its Existing in Finland*. VTT, (2012) Helsinki. Report VTT-CR-00554-12/FI. 27s. (in Finnish).
- [8] T. Rønning, *Freeze-thaw Resistance of Concrete. Effect of Curing Conditions, Moisture Exchange and Materials*. Doctoral Thesis, NTNU, Trondheim, 2001, p. 416.
- [9] J. Lahdensivu, S. Varjonen, T. Pakkala, A. Köliö, Systematic condition assessment of concrete facades and balconies exposed to outdoor climate, *J. Sustain. Build. Technol. Urban Dev.* 4 (3) (2013) 199–209.
- [10] BS 4027, *Sulfate-resisting Portland Cement*, British Standards Institution, 1996.
- [11] DIN 1164-10, *Zement Mit Besonderen Eigenschaften*, German Standards, 2008.
- [12] NBN B. 12-109, *Cement – Low Alkali Limited Cement*, Netherland Standards, 1993.
- [13] L. Salparanta, *Long-term RH Measurements in Two Bridge Decks*. VTT, (2007), p. 25 Helsinki. Report VTT-S-02777-07 (in Finnish).
- [14] *Repair guideline for concrete*. 2016. BY 41. Finnish Concrete Association. 115 p. (in Finnish).