ISSN online 2545-2819
ISSN print 0800-6377

Received: March 15, 2018
Revision received: Nov. 14, 2018
Accepted: Nov. 28, 2018

DOI: 10.2478/ncr-2018-0013

Alkali-silica Reaction in Finnish Concrete Structures

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ABSTRACT
Even though natural phenomena do not abide to borders, Finland has traditionally been considered an alkali-silica reaction (ASR) free country. This is due to exceptional quality of the mostly course crystalline igneous rocks. However, during the last few years dozens of cases of ASR have been reported. The scope of this study was to study the occurrence of ASR, and to find out the initiation time of the reaction in resent investigations of Finnish concrete structures. ASR is found occurring all over Finland. The reacting aggregates consist of rock types, which are considered relatively stable or low reacting in literature.

Key words: concrete, alkali-silica reaction, initiation time.

1. INTRODUCTION

In Central Europe and Scandinavia, alkali-aggregate reaction typically occurs in massive concrete structures such as bridges and dams, as well as in concrete roads and parking buildings. Despite the similarities between the bedrock of Sweden and Finland, unlike Sweden, Finland has been considered an alkali-silica reaction (ASR) free country, due to the exceptional quality of its rock [1]. More than half of the bedrock in Finland consist of granitoids, usually considered non-reactive or low reactive. However, the first published case of ASR was reported already in 1994 [2] and dozens of cases have been reported during the last few years [3, 4, 5]. VTT Research Centre made an initial survey of the occurrence of alkali-aggregate reaction in Finland. They gathered 56 cases reported during the years 1996-2011, these were mostly bridges and houses [3]. After the initial survey, 27 new cases out of 97 bridges have been reported [5].

The reacting rocks in Finland are not unlike the Swedish reacting rocks, reported for example by Appelquist et al in 2013 in their article Alkali-silica-reactivity of Swedish aggregates used for concrete [6]. Among others, some of the rocks from the Schist Belts of Southern Finland and Tampere region, which have caused ASR problems in Finland, are very much alike gneissic or fine grained, schistose rocks mentioned by Appelquist et al as being alkali-silica reactive. From what Appelquist has later presented, for example in the 2017 Euroseminar for Mineralogy of Building Materials [7], it looks like some of these rocks derive from the Svecocarelian (or Svecofennian, as it is often called in Finland) orogeny, just like many of the rocks in Finland associated with ASR. Hence the differences between the the neighbouring countries may be more in the nomenclature than in actual composition or petrogenesis of the reacting rocks. Therefore, it should be just to compare the two countries.

The scope of this study was to survey the occurrence and find out the initiation time and the progress of alkali-silica reaction in resent cases in Finnish concrete structures.

2. ABOUT ALKALI-SILICA REACTION

In alkali-aggregate reaction (AAR) the alkalinity of hydrated cement causes expansion of the aggregate in the concrete [8, 9, 10]. AAR has been traditionally divided into three different groups based on the reaction mechanism [11], but the division and even existence of some of the mechanisms has since been much debated and only alkali-silica reaction (ASR) has been deemed causing concrete expansion [12, 13, 14]. The ASR is the most common form of AAR [15]. In order for the ASR to take place, the reaction requires reactive silica-containing aggregate, a sufficient amount of alkali ions, calcium hydroxide and a minimum of 80% of relative humidity of concrete [10, 16]. Relative humidity of the concrete and expansion of ASR gel over time has been studied by Poole [17]. According to his studies, expansion of ASR gel starts to grow slowly as early as RH 50%. After RH 80% expansion will start to grow rapidly, see fig. 1. The environmental factors influencing ASR in Finland have been explained by Holt and Ferreira [18].

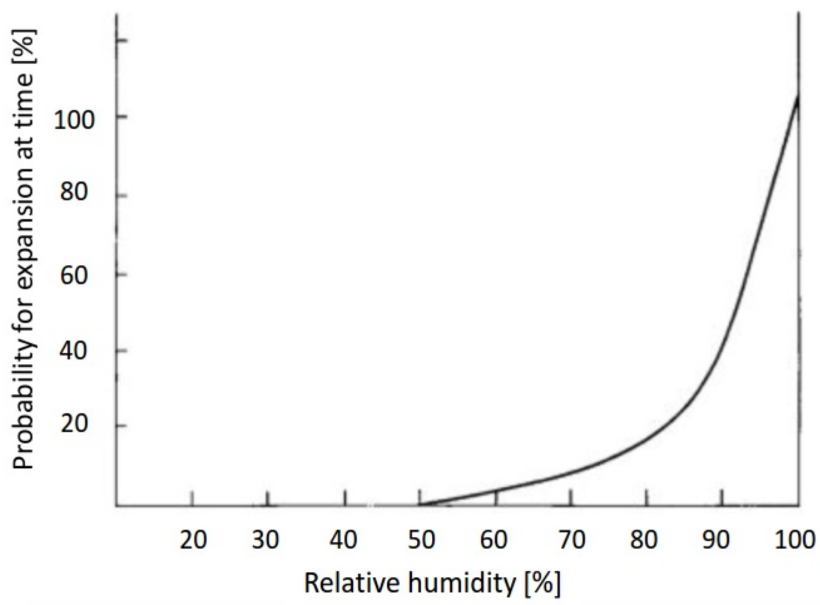

Figure 1 – The effect of relative humidity of concrete to the expansion rate of ASR [17].

ASR is a heterogeneous chemical reaction, which takes place in the aggregate particles between the alkaline pore solution of the cement paste and reactive silica in the aggregate [10]. The pore water must contain sodium (NaOH) and potassium (KOH) hydroxides and the aggregate must contain minerals with low resistance to alkalinity [15]. The reaction forms alkali-silica gel, which has the property of absorbing lots of water from the surroundings, causing the volume of the gel to grow, which leads to internal pressure of aggregate and finally also in the pore system of concrete. When the internal pressure exceeds the tensile strength of concrete, cracks appear in the concrete structure allowing the relatively soft gel to extrude through them [15, 19], see fig. 2. Far advanced ASR can be detected by naked eye from cross section of concrete sample, see fig. 3.

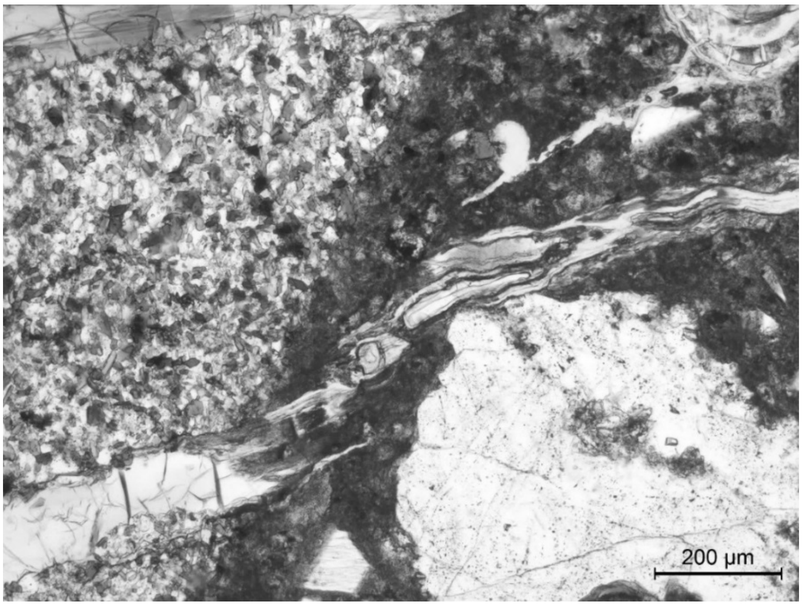

Figure 2 – Alkali-silica gel filling a crack propagating from the reacting aggregate the crack in concrete.

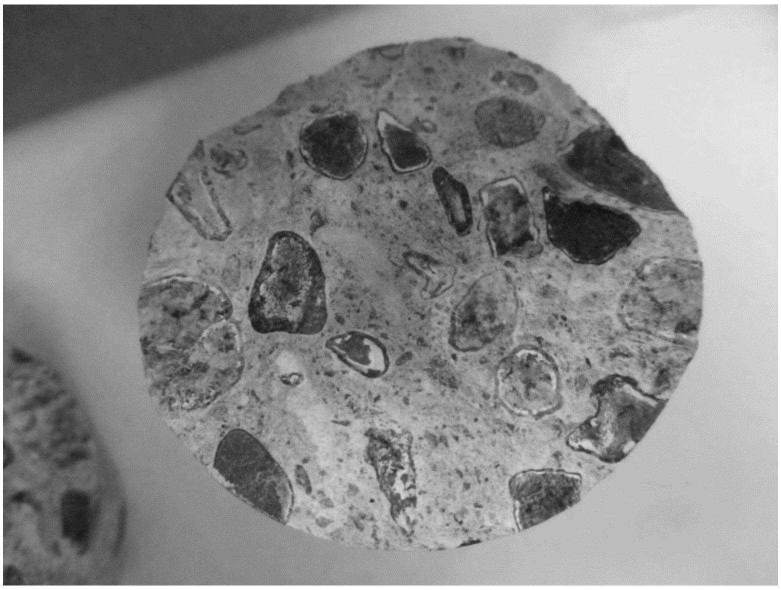

Figure 3 – Far advanced ASR can be seen as a dark reaction rim on the margin of the aggregate particles.

ASR generally results in slow degradation of concrete. The deterioration rate is influenced by prevailing conditions (i.e. temperature and humidity) as well as the type of aggregate and cement. In the case of silica bearing rocks, ASR may develop as soon as in 2-5 years. All aggregate containing silica, may potentially be reactive. However, differences in the crystal structure, density and grain size affect the reactivity. Different classifications for the reactivity of minerals and aggregates have been suggested by various authors over the years. Reactive aggregate types from all over the Europe have been listed among other by the RILEM technical committee [20]. AAR has been reported to occur also with highly stable rocks such as granite, quartzite and sandstone [19]. The most commonly suggested reacting aggregates, when it has been identified, in the previously reported cases in Finland, are schists, quartzites, gneisses, and granites [6, 7, 8]. With blended cements containing substitute cementitious materials like blast furnace slag (BFS) and pulverized fly ash (PFA), AAR is less common since fewer reacting alkalis are generally involved than with Portland cement (OPC) [22, 23, 24, 25, 26, 27, 28]. With small amounts of reactive silica, the expansion caused by the ASR is high. After 20% of silica content the expansion is lower, see fig. 4. This means, that varying the silica content in concrete, it is possible to lower the risk of ASR in new concrete construction [15]. Obviously, in existing concrete structures studied in this paper, content of concrete is what it is.

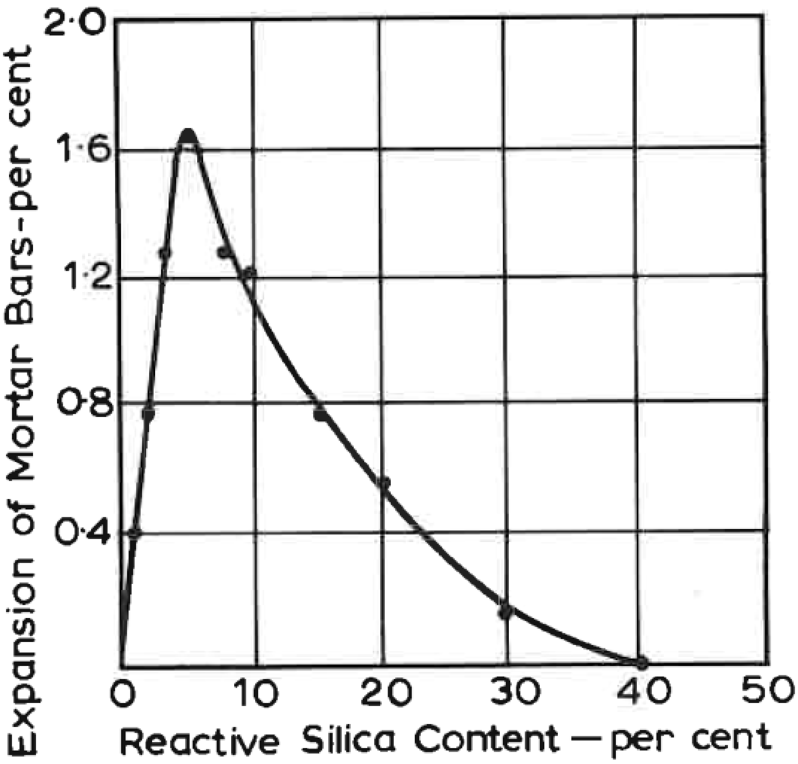

Figure 4 – Dependence of the expansion reaction in function of the silica content [15].

A concrete structure suffering from ASR typically shows discolouration due to surface moisture, irregular pattern cracking, swelling and oozing of a gel-like reaction product from the cracks [15]. The visible damage from ASR resembles the cracking caused by frost attack and often coincides with it [29]. The most significant difference between ASR and freeze-thaw damage is the pattern of cracking, which in the case of freeze-thaw damage is most intensive close to the outer surface and loses intensiveness with depth. ASR cracking begins deeper inside the concrete and produces a more regular cracking pattern across the entire concrete structure [30].

The state of the art method in, identifying ASR in a laboratory, is optical microscopy [31, 32, 33]. In some of the cases, recognizing mineral phases or reaction products with a SEM-EDX may be needed. The standard practice, most commonly followed in Finland, for the optical microscopy of hardened concrete is the ASTM C856 [34]. However, the standard does not cover fluorescence microscopy, which is a commonly used aid for recognizing porosity and cracking in concrete and aggregate.

3. RESEARCH DATA AND METHODOLOGY

The research data consists of 15 condition investigation reports and 84 thin section analysis reports, made during the years 2005-2017, in which ASR had been identified. The basic aim of a condition investigation is to produce information about the factors affecting the condition and the performance of the structure, and to consequently produce information about the need and the options for repair of the building or the structure for the owner. Damage to structures, as well as the degree and extent of damage, due to various degradation phenomena, can be determined by a comprehensive systematic condition investigation [35, 36]. The thin section analysis facilitates recognizing the degradation phenomena, causing the damage found in the condition investigation. However, the lack of common reporting practises complicates comparing the data, even if the analysis done following the same standard practice.

In this study the most important information surveyed from the condition investigation reports and thin section analysis reports was:

- Geographical location of the concrete structure
- Age of the concrete structure when ASR was detected
- The findings of the thin section analyses (reacting particles and cement type), number of reports was 84
- Tensile strength of concrete, number of samples was 71
- Compressive strength of concrete, number of samples was 29.

The factors affecting the development of ASR were studied in a literature review. The research material combined from condition investigation reports is quantitative by nature. This data has been studied with statistical analysis.

4. RESULTS AND DISCUSSION

4.1 Occurrence of ASR

Of the 84 cases, in which ASR had been found, 16 were facades and balconies, 23 bridges, 6 swimming pools and 7 other concrete structures. Most of the cases were in Oulu (16), the capital area (15) and Tampere (5), see fig. 5. ASR cases are not concentrated in one geographical area, but spread across Finland. ASR is mostly detected in the areas where there is built environment. Therefore, in Lapland where there is less built environment and renovation activities, there has been no reported data on ASR.

Figure 5 – The locations of detected ASR cases.

4.2 Initiation time for ASR

Average age and standard deviations of different concrete structures are presented in table 1. The age of the structure has been calculated from the year the condition investigation, in which the ASR was reported, has been conducted. Condition investigations of the structures were carried out in order to assess the repair needs of the structure, not specifically in order to find ASR. Some of the investigations were initiated because of visible deterioration, e.g. corrosion damage of reinforcement, but other structures were surveyed within a fixed-term monitoring. Therefore, the real initiation time for ASR is shorter than shown in table 1 and the age does not fully correlate to the emergence of visible deterioration.

Table 1 – The number of ASR cases and the average initiation age of structures.

Structure	Building years	Average age [years]	Standard deviation [years]	Number of cases
Facades and balconies	1919-1990	37	17	16
Bridges	1925-2002	44	15	23
Swimming pools	1960-1980	42	8	6
Others	1901-1995	47	31	7

As seen on the table, the structures have been built during a very long period of time. The first structure was built in 1901 and the newest one in 2002. Therefore, it is obvious that the standard deviation of ASR detection year is very large.

4.3 Cement type

There's variation in the reporting practices and accuracy in respect of cement type, and it is probable the substitute cementitious substances have not been mentioned in all reports, even if they have been used. Cement type was reported in 75 thin section analyses. The cement type was Portland cement (OPC) in 57 cases, OPC blended with blast furnace slag (BFS) in 15 cases and OPC blended with pulverized fly ash (PFA) in 3 cases, see fig. 6. Similar results on cement type have been found in [7]. It must be noticed, that all blended cements in Finland consists mostly of OPC. Fly ash or slag content in those cements is always mostly 20 %.

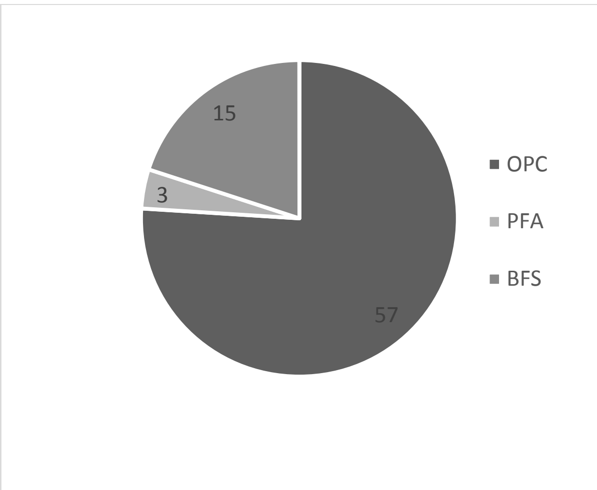

Figure 6 – Cement types detected in thin section analysis in ASR cases (n=75).

Alkali content of cement should be determined for estimating ASR possibility. Alkalinity of Portland clinker consists of sodium and potassium. Alkali content of cement can be determined as a Na_2O equivalent:

$$Na_2O_{EQ} = (Na_2O\ \% + 0.658\ K_2O\ \%) \quad (1)$$

According to some standards [37, 38, 39] Na_2O_{EQ} should be less than 0.60%. Na_2O equivalent in mostly used Finnish cement types varies between 0.80% (CEM I 42.5 N-SR) and 1.35% (CEM II/A-LL 42.5 R). Nowadays the most used cement type is CEM II/A-M 42.5 N with 1.10% Na_2O_{EQ}. The most typical concrete grade is C30/37 with 300 kg/m^3 minimum amount of cement. Thus, it is obvious that Finland has a high possibility for ASR.

4.4 Reactive aggregate

Reactive aggregate is only occasionally reported in thin section reports in Finland. This could be due to different reasons: the reacting particles may not be present in the studied thin section, the reacting particle may be too small to be reliably identified to a specific rock type, or there may be differences in the reporting practises between the laboratories or petrographers. Whenever the aggregate is identified it is usually a granite or a metamorphic rock such as a gneiss, a quartzite or a schist. The unexpected dominance of granites may be due to granitic gneisses or migmatites being mistaken for granites, or the typical, micro-cracking, unrelated to ASR, of granites. These are similar to the aggregates reported in [7]. These are also the most common rock types found in the Finnish bedrock. As can be seen in fig. 7, Finnish bedrock is relatively metamorphosed thoroughly. Most of the aggregate used at the time the surveyed structures were built is natural or crushed rock from glacofluvial deposits. However, since the mean glacial transport distances are mostly less than 5 km [40], a correlation to the local country rocks can be expected.

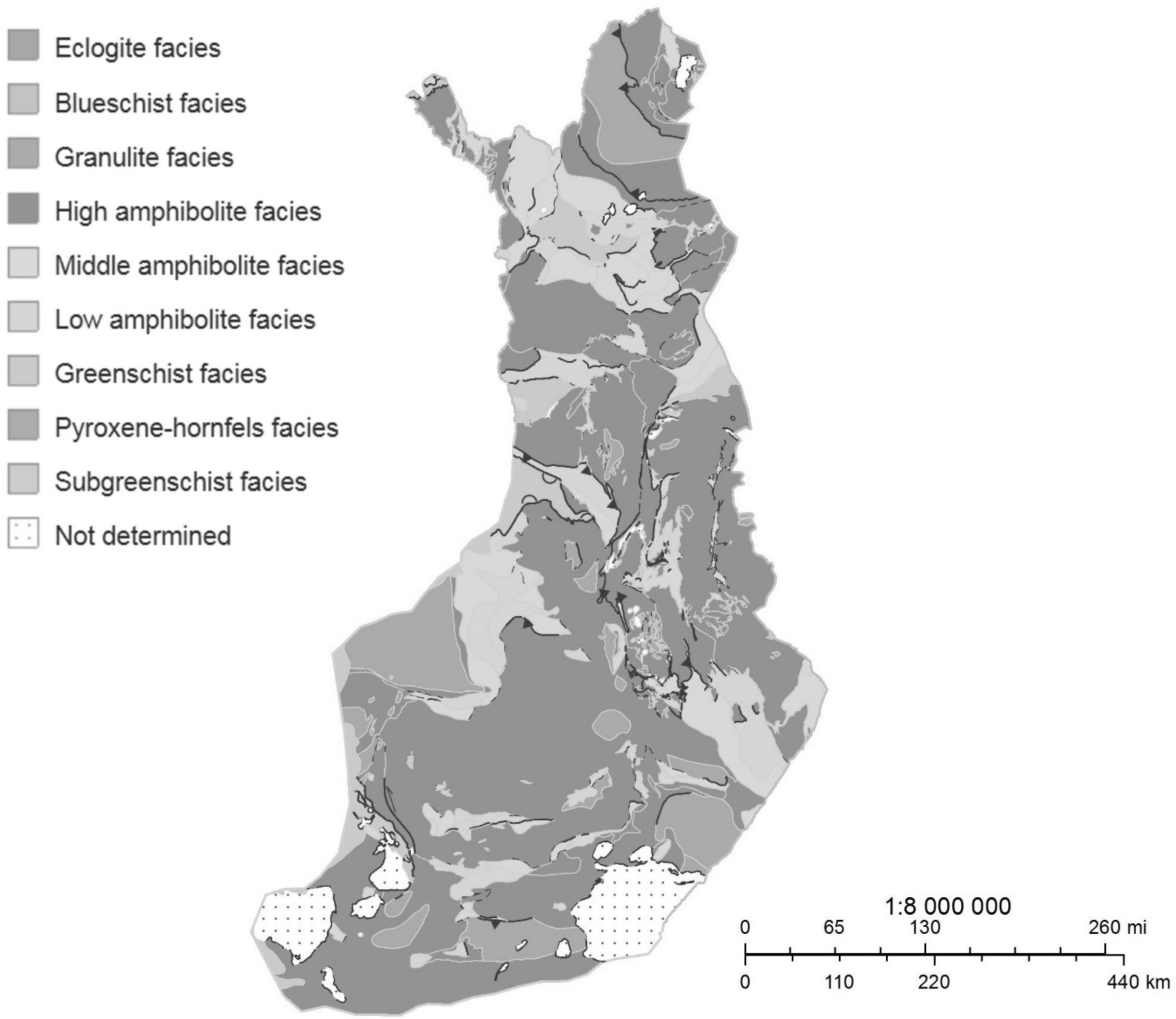

Figure 7 – Metamorphism of Finland from [41, 42].

4.5 Tensile strength of concrete

ASR causes cracking in concrete. Therefore, it affects the tensile strength of concrete rather than the compressive strength. Tensile strength test results were available from three swimming pools, see table 2. All tests cores were drilled towards to the smallest dimension of the structure.

Table 2 – Tensile strength results from three swimming pools.

Swimming pool	Tensile strength Min [MPa]	Max [MPa]	Number of samples	Results ≤ 0.5 MPa [No.]	Results ≤ 0.7 MPa [No.]
A	0.7	3.6	36	0	1
B	0.4	3.0	17	4	3
C	0.4	3.1	18	2	1

ASR can be reliably detected from thin section analysis, but the degree of ASR can be found out with tensile strength test. Observation of ASR gel does not indicate how the aggregate or concrete will crack [24]. Therefore, parallel test methods, thin section analyses and tensile strength tests are needed to ensure ASR in concrete structure. As seen on table 2, those swimming pools have also serious problems with ASR in spite of the number of relatively good tensile strengths.

4.6 Compressive strength of concrete

A total of 29 compressive strength tests were carried out according to the SFS-EN 12390-3 standard. Seven samples were cut in more than one part to determine the variation in compressive strength of concrete at different depths. The compressive strength of concrete was, on average, 61.5 MPa and standard deviation 11.4 MPa. Thus, unlike the tensile strength tests, the compressive strength tests of concrete did not indicate disintegration of concrete. Disintegration of concrete weakens the bond between the aggregate and the cement paste which affects the tensile strength of concrete before its compressive strength. This might be because compressive strength of concrete is not as good an indicator of disintegration as tensile strength.

5. CONCLUSIONS

According to research data, ASR is occurring all over Finland because of the relatively metamorphosed bedrock and the high alkali content of the cement. Reactive aggregates are classified to be relatively stable aggregates in literature, which explains why the occurrence of ASR has been taken round 40 years. However, the swimming pool environment is the most favourable for ASR, because of the constant high temperature and humidity. That is why ASR has been detected in swimming pools already around 30 years of age. Based on the research it is only a matter of time when ASR takes place in concrete structures, with potentially reactive aggregate, exposed to constant high humidity.

Optical microscopy of concrete thin sections is a reliable test method for detecting ASR in concrete. However, thin section analysis alone is not enough to ensure the progress of ASR in concrete. Thin section analyses should be supplemented with tensile strength tests. Tensile strength tests of concrete are found to be more representative for the state of disintegration of concrete than compressive strength tests.

ACKNOWLEDGEMENT

Authors will express their gratitude to Ramboll Finland Oy and WSP Finland Ltd Laboratory Services for allowing the usage of their data.

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