Prevention of ASR by use of low alkali OPC and silica fume. Field and lab studies from the Maridal culvert and the Storo bridge in Oslo, incl. assessment of residual expansion

Bård M. Pedersen (1), Eva Rodum (2), Marit Haugen (3), Jan Lindgård(4)

(1) Norwegian Public Roads Administration, Bergen, Norway, baard.pedersen@vegvesen.no

(2) Norwegian Public Roads Administration, Trondheim, Norway, eva.rodum@vegvesen.no

(3) SINTEF Community, Trondheim, Norway, marit.haugen@sintef.no

(4) SINTEF Community, Trondheim, Norway, jan.lindgard@sintef.no

Abstract

In 1999, the Maridal concrete box culvert with a total length of 340 m was built as part of the Tåsen tunnel in Oslo, Norway. The construction of the concrete culvert was closely followed up as part of a R&D program on early age concrete crack prediction. Hence, the concrete mixture, the construction work and the development of early age cracking are well documented. Natural aggregates from the Oslo area, known to be moderately alkali reactive according to laboratory testing and field experience, were used.

Field survey combined with microstructural analyses of drilled cores (performed in 2017) have confirmed that the use of OPC with relatively low alkali content (0.53 % Na_2O eq.) combined with addition of 5 % silica fume have prevented development of ASR. By corresponding field survey and microstructural analyses, it has also been verified that a similar aggregate combination has caused ASR in the nearby Storo bridge which was built in 1994. The exact binder composition of the Storo bridge is not known, but by comparing the alkali content from these two structures by use of a Cold Water Extraction (CWE) procedure it has been substantiated that the alkali content is 90 % higher in the Storo bridge compared to the Maridal culvert.

18 years of service is too short time to conclude whether the concrete composition used in the Maridal culvert has a potential to develop ASR or not. To assess the long-term potential of ASR, residual expansion testing according to the Canadian draft "UNB-CCT" method was initiated in April 2018. In this method, drilled cores stored at 38ºC are surrounded by a thin layer of an alkaline solution simulating the concrete pore water. The conclusion from this testing is that the potential for further reaction and expansion is limited.

***Keywords**: alkali content; cold water extraction; preventive measures; residual expansion*

1. INTRODUCTION

In 1999, the Maridal concrete box culvert with a total length of 340 m was built as part of the Tåsen tunnel in Oslo, Norway. The construction of the concrete culvert was closely followed up as part of the IPACS-project on early age concrete crack prediction, funded by the Brite Eu-Ram III program. Hence, the concrete mixture, construction and development of early age cracks are well documented [1]. Natural aggregates from the Oslo area, known to be alkali reactive according to Norwegian ASR methods [2] (petrographic examinations, mortar bar test results and concrete prism test results) and field experience, were used. At the time of construction, the knowledge on ASR was established in Norway, and the concrete mix design was in accordance with the Norwegian ASR regulations [3], allowing the use of any alkali reactive aggregates in combination with OPC for alkali levels up to 3.0 kg/m^3 (Na_2O eq.). The cement used for the culvert was an OPC with a relatively low alkali content of 0.53 % Na_2O eq., in combination with 5 % silica fume.

Figure 1.1: Outer wall and top slab during construction of the Maridal culvert in Oslo, Norway [1].

The nearby structure Storo bridge was renovated and enlarged in 1994. The new structural parts were cast by use of a concrete with similar aggregate composition as the Maridal culvert. The exact concrete composition including type of cement is not known for this structure. However, it has been substantiated through this study that the alkali content is significantly higher than in the Maridal culvert. In 2016 and 2017, both structures were visited and surveyed, and cores were sampled for microstructural and chemical analyses. For the Maridal culvert also residual expansion testing was carried out on some of the extracted cores. This paper describes the results and discusses the performance of the two structures.

Figure 1.2: The Storo bridge, southern side [4]

2. MATERIALS AND MIX DESIGN

2.1 The Maridal culvert built in 1999

The concrete mixture used for construction of the culvert is shown in Table 2.1. The concrete requirements were in accordance with the Norwegian Public Road Administration (NPRA) Handbook “General specifications 2. Standard specification texts for bridges and quays” [5], prescribing a water binder ratio ≤ 0.40 (calculated using an efficiency factor of 2 for silica fume), 3-5 % silica fume and 5 ±1.5 % air content.

Table 2.1: Concrete mixture from the construction of the Maridal culvert [1].

Materials	Content, kg/m^3
Norcem Anleggsement, OPC CEM I 52.5 (0.53 Na_2O eq.)	350
Silica fume	18
Plasticizer, Sika BV 40	4.0
Super plasticizer, Sikament 92	3.0
Air entraining agent, Sika AER	0.7
Natural sand 0/8 mm (absorbed water: 1.3 %)	953
Natural gravel 8/14 mm (absorbed water: 1.1 %)	206
Natural gravel 14/24 mm (absorbed water: 1.1 %)	658
Total effective water content	154.4
Effective water binder ratio, w/(c+2s)	0.40
Aimed air content (%)	5.0

The alkali content (alkalis from cement, admixtures and silica fume) is approximately 2.1 kg/m^3 (Na_2O eq.) and hence well below the general limit of 3.0 kg/m^3 Na_2O eq. valid at the time of construction (note: in 2017, the general limit was lowered to 2.5 kg/m^3). The level of preventive measures for this culvert was even “safer” than the requirements in the national guidelines due to addition of 5 % silica fume.

Microstructural analyses have shown that the sand and the coarse gravel both originates from the same gravel pit. A petrographic description and evaluation of the aggregate is as follows:

- The aggregate (sand and coarse gravel) is dominated by gneiss/granite, feldspathic rocks, dark rocks included volcanic rocks and siltstone/silt-claystone/marl. Sandstone and quartzite occur in less amounts. Mylonite, rhyolite, hornfels and limestone with and without impurities are represented as well.
- The alkali reactive rock types identified in the aggregate are siltstone, silt-claystone, marl, sandstone, mylonite and rhyolite, while hornfels and limestone with impurities are identified as possible alkali reactive rocks. The content of alkali reactive and possible alkali reactive rocks in the aggregate is about 30-35 %.

This aggregate, in particular the coarse fraction, is previously documented to cause moderate damages in structures when the alkali content is high enough [6]. The following results were obtained in accelerated mortar bar testing and concrete prism testing:

- Both the fine and coarse fraction of this aggregate was tested in the EU “PARTNER” project, labelled "N6" in [7]. The 52 weeks expansion from testing according to the Norwegian 38ºC concrete prism test [2] was 0.076, considerably higher than the critical limit of 0.040 % [7].
- A mortar bar test (1N NaOH, 80ºC, [2]) resulted in an expansion of 0.18 % after 14 days of exposure, well above the critical limit of 0.11 % that applies for mixtures of fine and coarse aggregates [8].

2.2 The Storo bridge built in 1994

As is often the case for old structures, it has not been possible to verify the cement type, the origin of the aggregate and mix design that were used in this structure. It has been claimed by people being involved with the construction works that the Storo bridge was built using a concrete mixture being similar to the concrete mixture of the Maridal culvert. The concrete requirements were most likely equal to that of the Maridal culvert, with one exception: In 1994 there were no national ASR regulations and hence no requirements on preventive measures in the form of low alkali cements or use of silica fume, fly ash or slag. Based on this, we can assume the following specifications:

- Effective water binder ratio, w/(c+2S): maximum 0.40
- Silica fume: 3-5 weight % of cement
- Air content: 5 % (±1.5 %)

Aggregates: Based on microstructural analyses of the cores it has been verified that the aggregate used in this structure is of "similar rock types and with similar reactivity" as the aggregate used in the Maridal culvert. It has, however, not been verified whether these two aggregates are from the exact same gravel pit or not.

Cement type: It is not known which cement type that was used, but based on information about the Norwegian cement market in 1994 it is most likely an ordinary Portland cement (CEM I), either similar to the cement used in the Maridal culvert (with a Na_2O eq. of 0.53 %) or a high-alkali cement with Na_2O eq. in the order of 1.2 %. To gain more information regarding the alkali content of this concrete, chemical analyses were carried out both on cores extracted from the Maridal culvert and the Storo bridge, see Section 2.3.

2.3 Examination of alkali content by use of Cold Water Extraction (CWE)

Chemical analyses by use of Cold Water Extraction (CWE), as described by Plusquellec et al. 2017 [9], were performed for concrete extracted both from the Maridal culvert and the Storo bridge to compare these. The results are summarized in Table 2.2. The measured alkali content of the samples is assumed to represent the available alkali content of the pore solution at the time of extraction. Note that the alkali content from the Tåsen culvert is almost identical to the theoretical value calculated from the concrete mixture (2.1 kg/m^3 Na_2O eq.). It is not known how much of the measured alkalis that originates from the cement, normally only 50-70 % of these alkalis will be available in the pore solution according to Plusquellec et al. 2017 [9], depending on the type of binder (the highest level of alkalis, i.e. 70 %, is expected available for OPC). It is thus likely that alkalis released from the aggregates have contributed to the measured alkali content. However, since the aggregates are similar in these two concretes, we can still compare the results. It is therefore reasonable to assume that the total alkali content for the Storo bridge is in the order of 90 % higher than for the Maridal concrete, i.e. approx. 4.0 kg/m^3 (Na_2O eq.). This further implies that the cement used was an OPC with an alkali content of approximately 1.1 % (Na_2O eq.). Since the Storo bridge also has developed some ASR (see 3.2), some alkalis have most likely been absorbed in the ASR gel. The original alkali content of the Storo bridge concrete is thus assumed to be a little higher than 4.0 kg/m^3 (Na_2O eq.).

Table 2.2: Measurement of alkali contents by the CWE-method. Mean values of four samples from two cores (Maridal) and two samples from one core (Storo) [10].

Structure	[Na] pore solution, mol/l	[K] pore solution, mol/l	Alkali content of the sample, kg/m^3, Na_2O eq.
Maridal culvert	0.34	0.30	2.3
Storo bridge	0.55	0.65	4.2

Based on the results and discussions in Sections 2.2 and 2.3 the following has been substantiated: The concrete used in the Storo bridge is rather similar to the concrete used in the Maridal culvert, with one important exception: The cement used in the Storo bridge had a significantly higher alkali content compared to the cement used in the Maridal culvert.

3. FIELD AND MICROSTRUCTURAL EVALUATION OF STRUCTURES

3.1 The Maridal culvert after 18 years of service

3.1.1 Field survey

In June 2017, the Maridal culvert was visited and surveyed, and six cores were drilled from four different sections of the culvert. Typical crack patterns caused by early age hydration heat effects in a wall-on-slab structure are shown in Figures 3.1 and 3.2. Vertical cracks in the wall are caused by external restraint from the slab during the cooling phase of the wall. Cracks with crazing pattern (Figure 3.2) are caused by temperature gradients over the cross section of the (warm) wall shortly after demolding. Drying shrinkage may also produce (or further develop) the crazing, as can ASR if present. The crack widths varied from very fine cracks 0.03 mm up to 0.45 mm. These examples are typical for the initial state of cracking of a new structure, just a week or two after casting. The origin is cement hydration and subsequent heat generation.

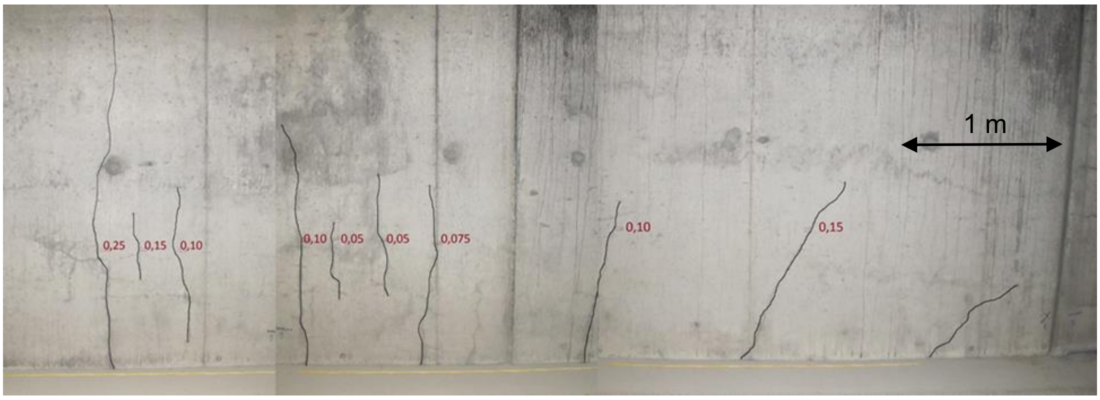

Figure 3.1: Visual assessment of wall in the Maridal culvert, right half of section 42. Main cracks intensified on the photo, crack widths (in mm) are drawn on the photo [11].

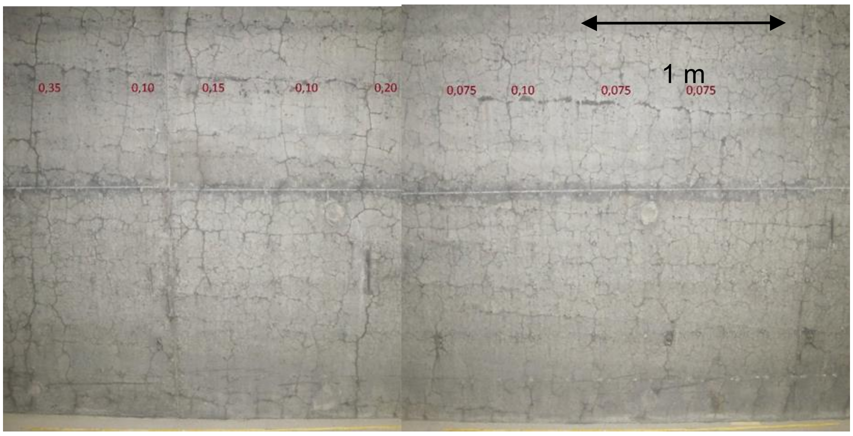

Figure 3.2: Visual assessment of wall in the Maridal culvert, part of section 38. Crack widths (in mm) are drawn on the photo [11].

3.1.2 Microstructural analyses

Visual examinations of the six drilled cores showed no signs of ASR. For one of the cores from section 42 further analyses were performed; microstructural analysis of one fluorescence impregnated plane polished section prepared from one half-core (after sawing one core into two parts) and of one thin section prepared from the other half-core. Two photos of the plane polished section, in ordinary and UV light, respectively, are shown in Figure 3.3, while two photos of the thin section are shown in Figure 3.4.

The results from the microstructural analyses can be summarized as follows [10]:

- Plane polished section (Figure 3.3): Some cracks in the cement paste, a few cracks in aggregates and very few cracks running from aggregates into the cement paste. No appreciable signs of ASR.
- Thin section (Figure 3.4): Some micro-cracking, no coarse cracks. Some ettringite and a few particles of undispersed silica fume were observed. No signs of ASR.

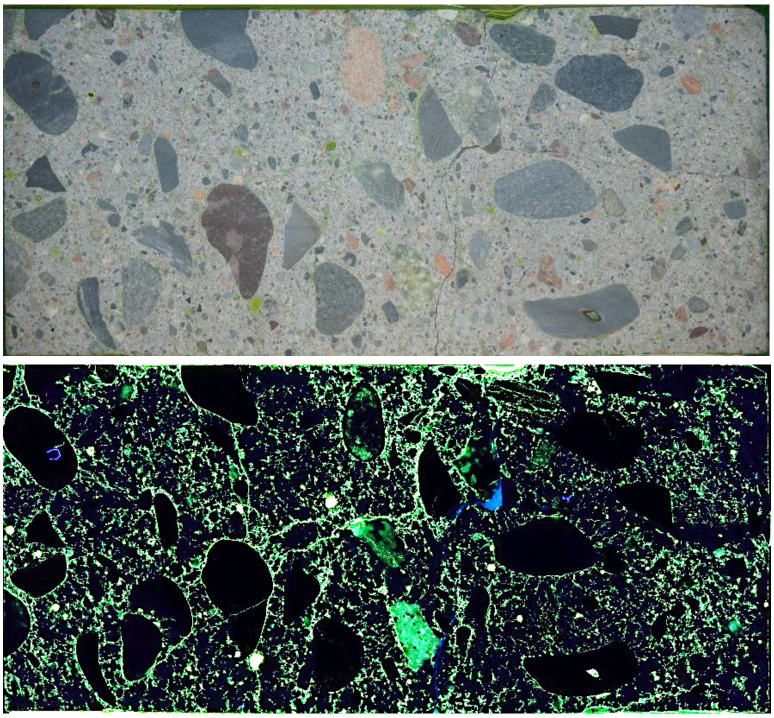

FIGURE 3:3: Plane polished section from wall section 42, in ordinary and UV-light. The length of the section is 200 mm, surface to the right. *Comment: The core was drilled through a crack starting at the surface (crack width 0.25 mm), then turning parallel to the surface in a depth of about 80 mm. Due to this cracking, the outer part of the core was broken during the drilling process. The core was thus glued before preparing the polished section, with a non-fluorescence epoxy. These cracks can therefore only be observed in the upper picture (but not in the lower picture). [10].*

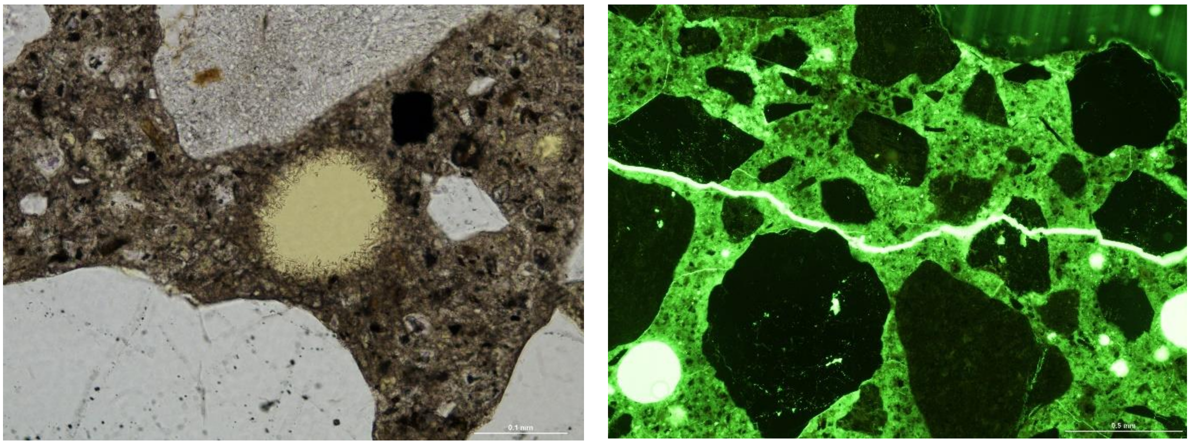

Figure 3:4: Thin section details. No signs of ASR were observed. Left: Ettringite in a small air void. Right: Crack in the cement paste. [10].

3.2 The Storo bridge after 22 years of service

3.2.1 Field survey

Parts of the Storo bridge in Oslo was built in 1994, including the railing structure. Due to suspected progressing ASR, this structure was visually examined in October 2016, and three cores were drilled. As can be seen in Figure 3.5 the surface cracking of the railing appears as crazing or map cracking. The crack widths varied between 0.03 and 0.15 mm. The cracking indexes, defined as "summarized crack widths along a line divided by the length" [4], varied between 0.041 and 0.062 % for the different fields of the bridge railing. The calculated indexes were evaluated to be of low degradation grade according to a classification system developed within a Norwegian research project [12]. No significant differences between horizontal versus vertical lines were found.

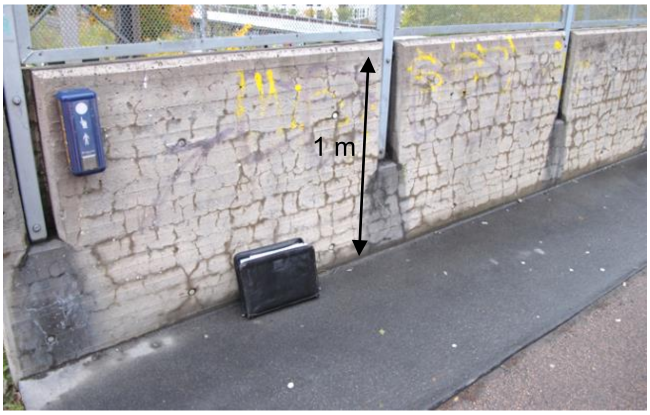

Figure 3.5: Visual assessment of the railing of Storo bridge, phase to the north [4].

3.2.2 Microstructural analyses

By visual examination of the cores, two of the three cores showed signs of ASR. For one of the cores further analyses were performed; microstructural analysis of one fluorescens impregnated plane polished section prepared from one half-core and of one thin section prepared from the other half-core. Two photos of the plane polished section, in ordinary and UV light, respectively, are shown in Figure 3.6, while two photos of two thin sections are shown in Figure 3.7. The conclusions of the analyses can be summarized as follows [10]:

- Plane polished section (Figure 3.6): Cracks in some aggregate particles, some cracks running from the aggregate into the cement paste. A white precipitation product found in some air pores.
- Thin section (Figure 3.7): Many micro-cracks and fine cracks. Alkali-silica gel observed in several air pores and in cracks, both in the aggregate particles and in the cement paste. ASR has led to internal cracking of the concrete.

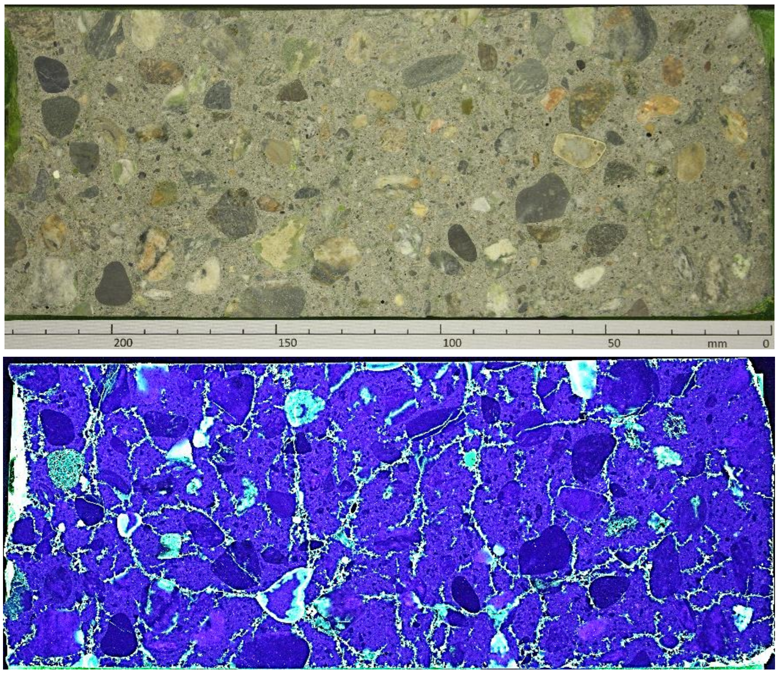

Figure 3.6: Plane polished section from Storo bridge, in ordinary and UV-light. The length of the section is 230 mm, surface to the right [10].

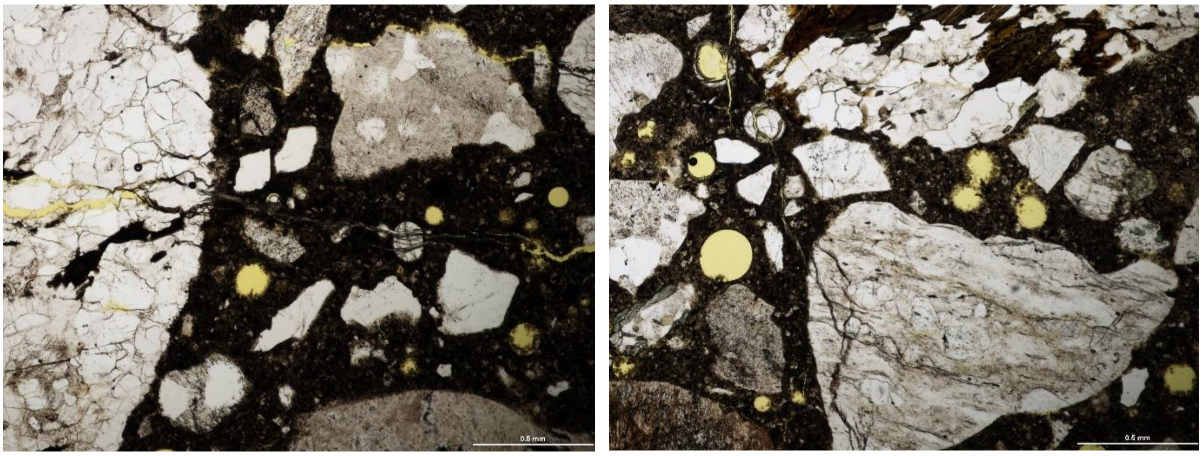

Figure 3.7: Thin section details. Left: Alkali-silica-gel in a crack running from a quartz-rich rock. Air void in crack filled with alkali-silica gel. Right: Alkali-silica gel in a crack running from a mylonite rock. Air void in crack filled with alkali-silica gel [10].

3.3 Conclusions based on field and microstructural examination

Based on the presented field survey and laboratory results (microstructural analyses in plane polished sections and thin sections) there are obviously differences in performance for the two structures: The Storo bridge built using an OPC with an alkali content of approximately 1.2 % (Na_2O eq.) + 3-5 % silica fume (assumed binder composition) shows clear signs of ASR after 22 years of service. On the other hand, the Maridal culvert built using an OPC with a much lower alkali content of 0.53 % (Na_2O eq.) + 3-5 % silica fume (known binder composition) shows no appreciable signs of ASR after 18 years of service. Both structures have cracks in field that look "suspicious". However, the cracks on the Maridal culvert were primarily developed at a very early age [1]. It should also be noted that the cores from the Maridal culvert was taken from the inner side of the culvert not exposed to direct rainfall, while the cores taken from the Storo bridge is from the railing directly exposed to rainfall.

4. ACCELERATED RESIDUAL EXPANSION TESTING

4.1 Concrete from the Maridal culvert

18 years of service is a bit short time to conclude whether the concrete from the Maridal culvert has a potential to cause harmful ASR or not in the long run. To test the potential of ASR, residual expansion testing by the Canadian "UNB-CCT" method [13] on three cores (ø94 mm x 300 mm) was initiated in April 2018. In this method, the cores stored in sealed containers at 38ºC, are "surrounded" by a "thin layer" of an alkaline solution simulating the pore water solution. The alkali concentration (Na and K) of this alkaline solution was calculated based on chemical analysis of extracted concrete by use of the CWE method described by Plusquellec et al. 2017 [9]. Ideally, this should result in a situation where the alkalinity of the pore water is in equilibrium with the liquid layer surrounding the specimens.

Expansion results up to 78 weeks of exposure are shown in Figure 4.1. As can be seen in the Figure, the specimens are expanding slowly at 38ºC.

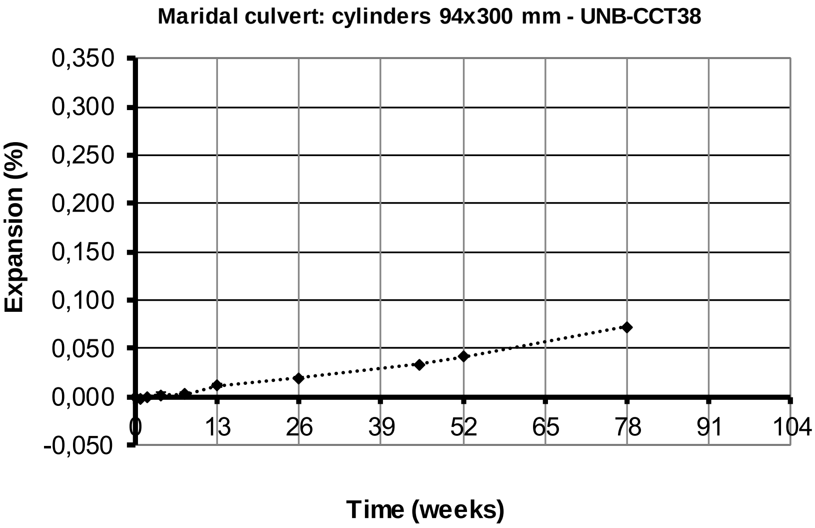

Figure 4.1: Residual expansion testing by the Canadian UNB-CCT test method. Mean values of three samples [12].

So, what can we learn from this plot? Should we expect that the concrete would react and expand in the long run or not? When exposed to 38ºC and 100% RH there is obviously some potential for reaction. The expansion level at 52 weeks is above the border of the 0.030 % limit given by the Norwegian regulations when running performance testing by use of the concrete prism test method [8]. However, the residual expansion test method is “more aggressive” than the CPT-method since there is no leaching of alkalis (or more likely a slight ingress of alkalis from the solution surrounding the sample). The results shown in Figure 4.1 have been compared with residual expansion results from another bridge with a more reactive concrete composition, see Section 4.2.

4.2 Comparison with the Nautesund bridge

The Nautesund bridge was built in 1959 and demolished in 2009, partly due to ASR. In connection to the demolition, a comprehensive R&D project was carried out, described in [14, 15]. Among other topics this included reconstruction of the concrete mixture (alkali content and aggregate type), residual expansion testing of extracted concrete from the bridge as well as concrete prism testing of freshly cast reconstructed concrete. Reconstruction of the old concrete was carried out according to the following procedure: a) separation of aggregate from concrete by use of liquid nitrogen and microwave, b) splitting into < 4 mm and > 8mm fractions by sieving, c) petrographic analysis and identification of the aggregate origin and d) estimation of cement content by use of TGA. Concrete structures built up to 1990 was mainly built using ordinary Portland cement from the national cement supplier Norcem, and the alkali content can be estimated based on historical data from Norcem. A more detailed description of the reconstruction methodology can be found in [10, 15].

The alkali contribution from the OPC being used has been estimated to be between 4.8 and 5.3 kg/m^3 (Na_2O eq.) [15]. The separated aggregate (sand and coarse aggregate) is consistent with the aggregate found in a local pit close to the bridge. It is dominated by quartzite, gneiss/granite and metarhyolite, while dark rocks incl. volcanic rock, quartz rich rock, feldspathic rock, quartzite and metasandstone occur in less amounts. The alkali reactive rock types identified are metarhyolite and metasandstone, while quartzite and quartz rich rock are identified as possible alkali reactive rocks. The content of alkali reactive and possible reactive rocks is about 35 %, i.e. at the same level as the aggregate used in the Storo bridge and the Maridal culvert [15].

Two freshly cast reconstructed concretes with OPC (“Mix 1” with 4.8 kg/m^3 (Na_2O eq.) and “Mix 2” with 5.3 kg/m^3 (Na_2O eq.)) and aggregates collected from the local pit used to cast the bridge, were tested according to the Norwegian CPT method (100x100x450 mm^3 prisms at 38°C/100%RH) [2]. Testing of residual expansion of the original bridge concrete was performed by two 38°C CPT methods; 1) the Canadian “UNB-CCT” method with alkaline solution (as described in 4.1) and 2) the Norwegian CPT (samples stored on grids above water, labelled "100 % RH") [2]. The latter included two series of specimens, i.e. sawn prisms (100x100x450 mm^3) and cored cylinders (ø145 mm x 300 mm). Some relevant results are plotted in Figure 4.2.

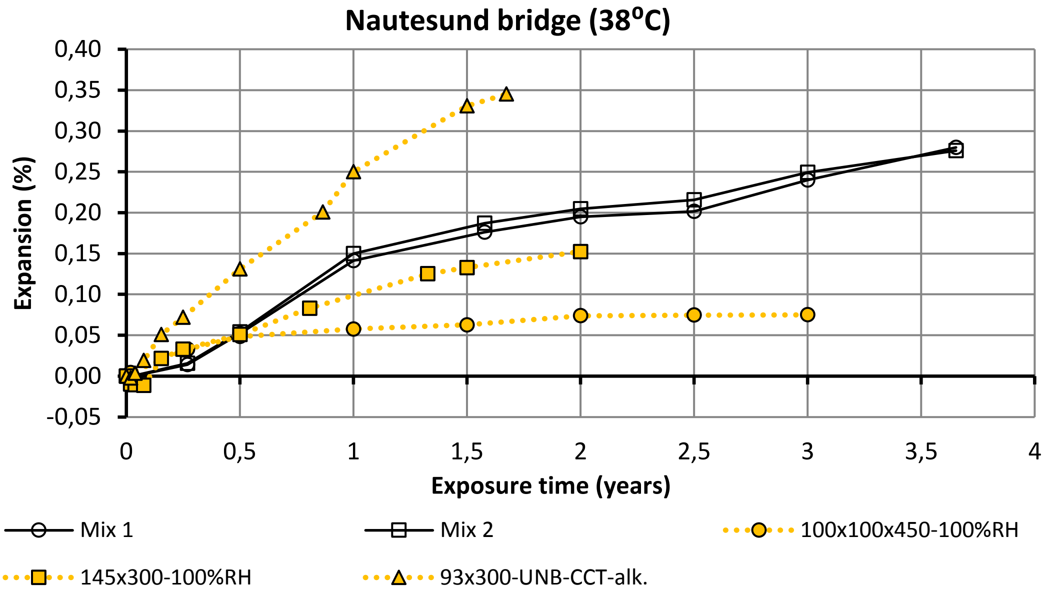

Figure 4.2: Test results from the Nautesund bridge, all samples exposed to 38 ºC. Black lines show results from accelerated testing of freshly cast reconstructed concretes, yellow dotted lines show results from residual expansion testing [12].

As seen from Figure 4.2, the accelerated residual expansion of the Canadian “UNB-CCT” cylinders (labelled "93x300-UNB-CCT-alk.") is 0.25 % at 1 year and still increasing. Accelerated residual expansion of sawn 100 mm prisms (labelled "100x100x450-100%RH") and ø145 mm drilled cylinders (labelled "145x300-100%RH"), tested according to the Norwegian CPT-method, show significantly lower expansion levels at all ages. The sawn prisms (with highest area/volume-ratio) is levelling off after six months of exposure at a relatively low expansion level, most likely due to lack of alkalis caused by leaching combined with further consumption of alkalis by the ASR-gel developed during the testing. The expansion potential for the freshly cast reconstructed concrete (100 mm prisms labelled “Mix 1” and “Mix2”) is significantly higher than the residual expansion of sawn prisms of original concrete (of same prism size), but much lower than the results of the “UNB-CCT” residual method with possibility of external alkali supply. The ø145 mm drilled cylinders are still expanding after two years of exposure but are tending to level off after 1-1.5 years of exposure.

It is interesting to note that the freshly cast reconstructed concretes and the two residual expansion test series, all exposed to 100 % RH, obtain equal expansion (0.05 %) after six months of exposure. After this point in time, the access to alkalis in the concrete pore water is controlling the further ASR expansion. Since the field concrete already (during 50 years of service) had developed ASR at the time of drilling, the "starting" alkali level in the pore water is lower (due to consumption of alkalis by the ASR-gel) compared with the freshly cast concrete. This is assumed to be the main cause for the earlier levelling off for the field concrete samples.

The comparison has shown that the “UNB-CCT” method, used for the Maridal-culvert, most likely is somewhat “conservative”. Hence, the probability for development of harmful ASR in the Maridal culvert is relatively low. Even though there might be a potential for long-term damages, it will be an extremely slow process due to the climatic conditions. The yearly average mean temperature in Oslo is only 7 ºC (with monthly average variations from -4 ºC to 18 ºC) and the average relative humidity (RH) is 74 %. The access to rainfall / water is also limited in the Maridal culvert.

5. CONCLUSIONS

Investigations of the Maridal culvert after 18 years of service have shown that the combination of relatively low alkali content and 5 % silica fume has prevented ASR, while a 90 % higher alkali content as exemplified for the otherwise similar concrete in the Storo bridge has caused ASR. There are some uncertainties regarding the time factor for the Maridal culvert, since the age was only 18 years at the time of the investigation (i.e. one cannot conclude that ASR will not develop in the future). Therefore, accelerated residual expansion measurements have been performed. The results indicate that the potential for future harmful ASR is limited.

6. ACKNOWLEDGEMENT

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