ELGESETER BRIDGE IN TRONDHEIM DAMAGED BY ALKALI SILICA REACTION: MICROSCOPY, EXPANSION AND RELATIVE HUMIDITY MEASUREMENTS, TREATMENT WITH MONO SILANES AND REPAIR

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Abstract
The design of Elgeseter bridge built in the period 1949 to 1951 is unique for Norwegian construction work in the 1950's and required optimal material proportions presented here. In the early 1990's deleterious Alkali Silica Reaction (ASR) was documented by use of micro structural analysis and explains the observed expansions and cracking of the concrete. Damage due to ASR occurs most intensely on western faces of structural elements exposed to rain water and in the middle of the river. In-situ measurements since 1995 have given important information on the concrete's relative humidity and the expansion rate of cracks. Relative humidity is generally high (100%) and cracks expand maximally 0.15 mm yearly. Tests with impregnation of mono silane on columns have given very promising results. One product with creamy consistency has reduced the relative humidity 5 cm from the surface to less than 80% and theoretically "stopped" or significantly reduced the ASR.

Introduction
Elgeseter bridge is probably the most thoroughly investigated concrete structure damaged by ASR in Norway. Before 1990 significant reduction of the only expansion joint in the road plate and cracking in other concrete elements were observed. First in the early 1990s, when ASR was accepted to be a common deterioration process in Norway, a reasonable explanation of the damage was obtained. The paper gives a chronological review of the construction of the bridge, materials, damage, results from research projects and the repair work in 2003.

Construction of Elgeseter bridge
Design
Elgeseter bridge was built in 1949-1951 as a continuous 200 m long reinforced concrete bridge with only one expansion joint in the northern end of the bridge. The expansion joint was designed to be 20 cm wide in 1950. Four 200 m long beams, two abutments and 8 rows each with 4 columns support the bridge plate. Columns in each row are supported by eight 22 m long foundation beams which are dogged down in the riverbed. Each foundation beam is supported by 78 timber stocks 12 – 20 m long. The two abutments are supported by several 15 m long concrete piles located above ground water level. Columns having a height of up to 10 m and a diameter of 80 cm are monolithic fastened to beams and foundations except the most northern row 9 which is mounted with steel plates fastened to the beams. Columns located in the river are protected against ice corrosion by 3 mm thick steel protection caps to about 0.5 m above high water level. The cost of the concrete bridge was 1.5 mill NOK in 1951, Knudsen [1].

Orientation
Elgeseter bridge is coordinated according to normal practice in the Road Directorate, as the following:

- Axe 1: Southern abutment
- Axe 2: first row of columns on the east bank.
- Columns: column 1 is located to the west and column 4 to the east
- Axe 3 – 8: columns in the river
- Axe 9: last row of columns on north bank
- Axe 10: Northern abutment

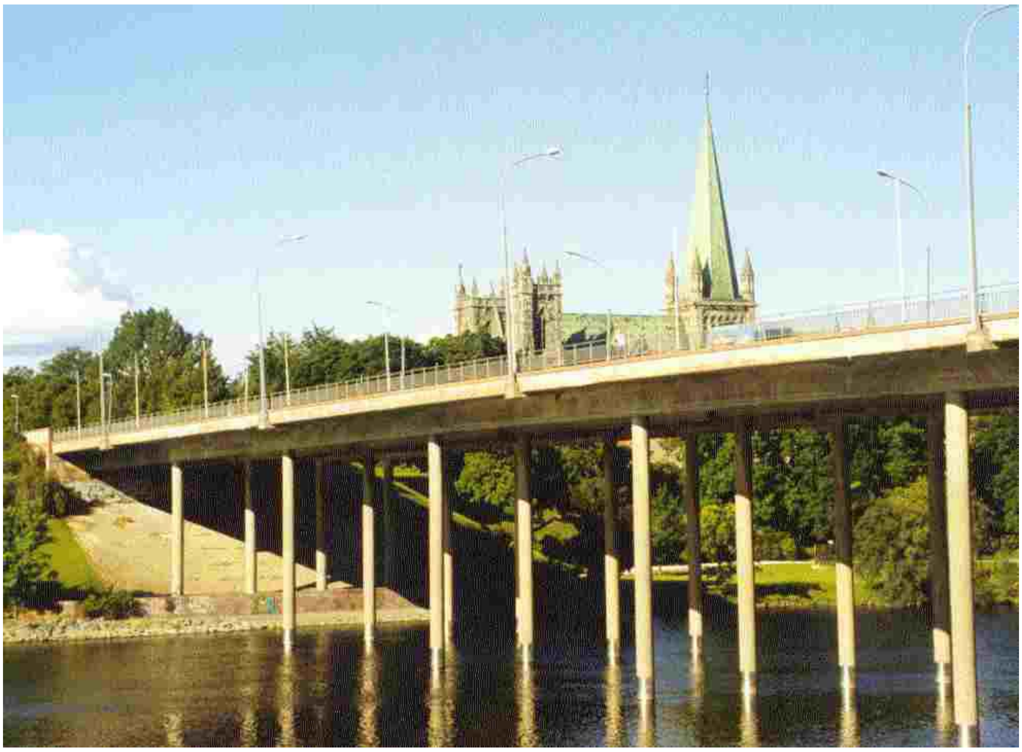

Figure 1: Northern part of Elgeseter bridge with Nidaros cathedral in the background.

Aggregates, cements and concrete mixes
In the 1950s Elgeseter bridge with its slender construction elements represented a technological and constructive challenge for the engineers. The uniform and high concrete strength required a quality and control system, which was not common at that time. Therefore, a rather large testing program was performed to find the best aggregate type, aggregate combination, cement type and optimal concrete proportions. In the following material combinations used for the construction of Elgeseter bridge are given [1].

Aggregates
It is interesting that marine aggregates at that time commonly used in Norway were not selected due to the risk of reinforcement corrosion. For the concrete in Elgeseter bridge the following combination of aggregates was used:

- Soeberg glaciofluvial fine gravel; fraction 0 – 16 mm

- Klett glaciofluvial coarse gravel from the river Gaula; fraction 15 – 35 mm

- Trolla crushed rock; fraction 3 – 15 mm (to compensate for the missing 4 – 16 mm fraction of the coarse gravel)

For columns the ratio fine/coarse/crushed = 50/28/22 were used and for abutments, plates and foundations the ratio 48/29/23 (more rich in stones).

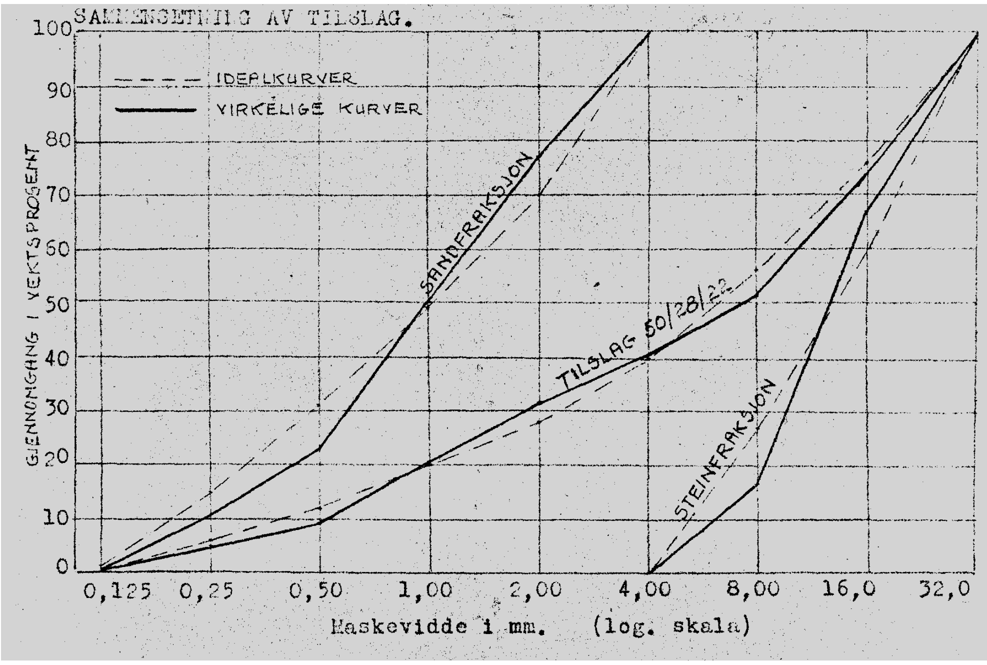

Figure 2: grading curves of aggregate combinations used for concretes in columns. X-axis is size fractions in mm and Y-axis is cumulative percent material passing the sieve. Dashed lines are ideal curves and full lines are actual curves.

Cements

Tests with Norwegian standard Portland cement produced in the two Norwegian cement plants “Dalen” and “Slemmestad” gave less compressive strength compared with Swedish and Danish cements. Therefore, a new Portland cement called standard –S was developed and produced at “Dalen” for the construction of Elgeseter bridge. This cement was more fine grained and contained more gypsum than normal standard cement at that time. The exact amount of added gypsum is unknown but the total sulfur content should be higher than required in the Norwegian cement standard at that time. The alkali content of cements is also unknown but is probably higher than 1 weight %.

Figure 3 shows the compressive strength of concretes with standard cement, standard – S cement, Danish white cement and Swedish cement [1].

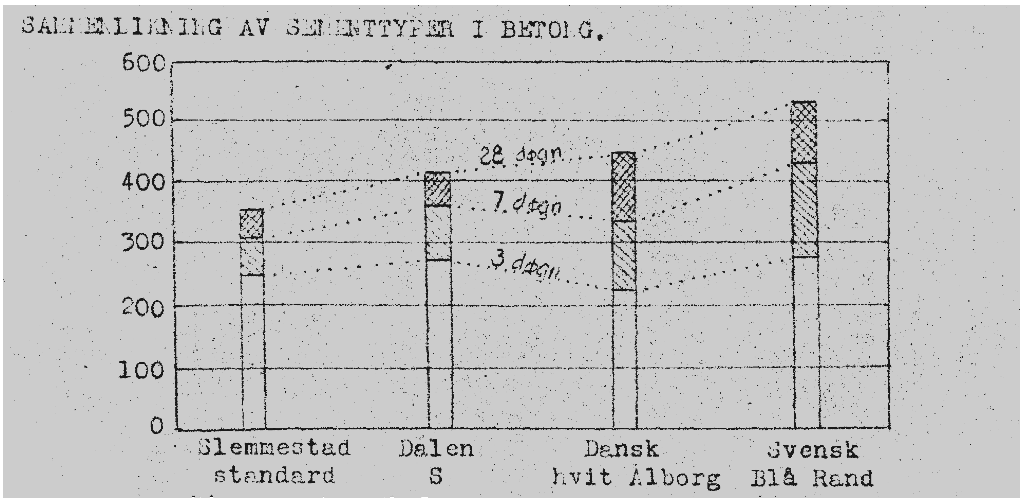

Figure 3: compressive strengths of concretes with four cements after 3 days, 7 days and 28 days hardening. Y-axis is compressive strength (kg/cm^2).

Additives

Air entrainment is added to all concretes to improve the mixing, reduce risk for separation and improve the frost resistance. Especially for columns located in the river frost resistance was important. Figure 4 shows test results of concrete without air entrainment and with 4.2 % air voids [1]. Note that concrete with 4.2 % air voids is frost resistant even after 200 freeze- thaw cycles. Up to today , frost damage has not been observed in any structural elements of Elgeseter bridge.

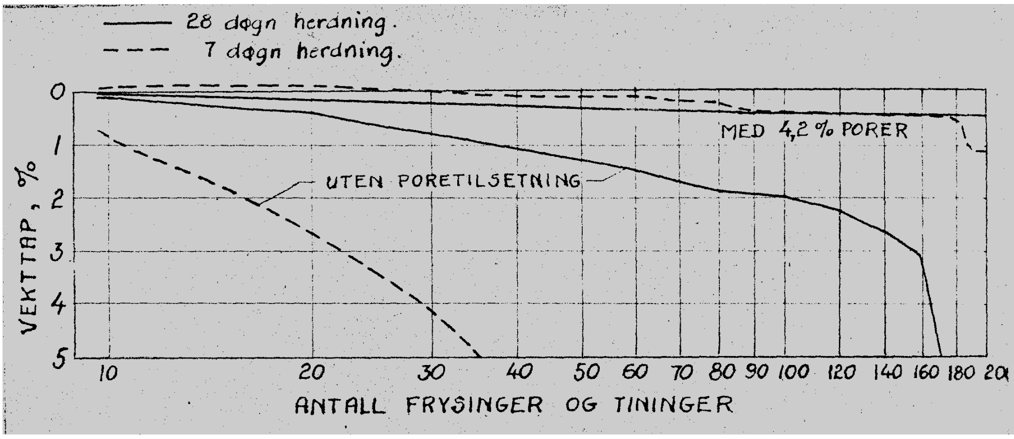

Figure 4: test results of concretes without air entrainment (*uten poretilsetning*) and with 4.2 % air voids from concretes hardened 28 for days (full line) and 7 days (dashed line). X-axis is number of freeze-thaw cycles and Y-axis is loss in weight %.

However, air entrainment reduced the compressive strength of the concrete with 6 % for each 1 % added air voids, which has to be compensated with increased cement content or lower water/cement ratio. Therefore, only about 3 % air was used in the final concrete mixes. DAREX AEA was probably the air entrainment product used for the concrete mixes (unknown chemical composition).

Concrete proportions

Table 1 gives concrete proportions used for Elgeseter bridge [1]. The material composition of abutments and beams (concrete quality A) is actual values from the construction work on beams (between columns 5 and 6). The values of columns (concrete quality AA) and foundations (concrete quality A) are excepted values calculated from the requirement given in the concrete work description.

Table 1:concrete proportions

Materials/parameters	**Abutments and beams**	**Columns***	**Foundations***
	Quality A	***Quality AA***	***Quality A***
Fine gravel (kg/m^3)	888	926	926
Coarse gravel (kg/m^3)	538	518	518
Crushed rock (kg/m^3)	426	407	407
Cement (kg/m^3)	350	450	400
Water/(active) (kg/m^3)	178	180	180
Water/cement-ratio	0,51	0,40	0,45
Air (%)	2,9	3	3
Density (kg/m^3)	2380	2482	2432
Construction concrete (m^3)	3150	200	450

*calculated by the author

Compressive strength

The Norwegian standard NS 427 valid in 1950 required the following 28 days compressive strength values (cubes 10 cm x 10 cm x 10 cm).

- Concrete quality AA:396 kg/cm^2 (39.6 MPa)
- Concrete quality A:319 kg/cm^2 (31.9 MPa)

NS 427 requires that 90% of test results fulfill these requirements. Figure 5 shows compressive strength results from control specimens during the construction period [1].

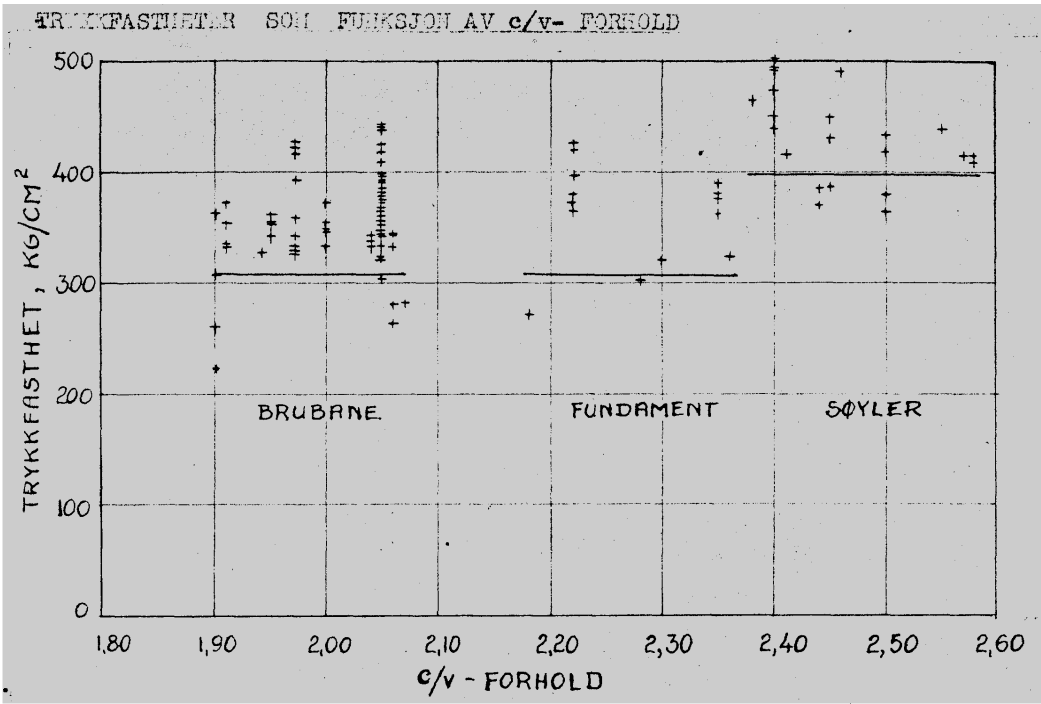

Figure 5: compressive strength from control specimens during the construction period. X-axis is cement/water –relation and Y-axis is compressive strength (kg/cm^2).

The variation on cement/water – relation seen in figure 5 is caused by adjustment of mix proportion to obtain strength requirement in the standard. The average compressive strength (28 dg) and variation coefficient is given in table 2.

Table 2: Average compressive strength (28 dg) and variation coefficient

Structural elements	N	Average Comp. Strength (Kg/m2)	Variation cof. (%)
Abutments, plate, beams	37	342 *(357)*	12.3 *(7.5)*
Foundations	4	391	7.1
Columns	22	408 *(434)*	16.2 *(10.6)*

Parentheses are exclusive results from the 15 July to 12 September 1950

In the period 15 July to 12 September 1950 lower compressive strength values were measured. Most of the strength values below the NS 427 requirements shown by horizontal lines in figure 5 are from this period. Research to find out the reason for the reduced compressive strength suggested a batch of cement to have caused the lower strength values. However, after 12 September 1950 compressive strength values were "normal" again. The variation coefficient varies from 12.3% to 16.2% for structural elements in Elgeseter bridge. For Swedish bridge building in 1942 a variation coefficient 7.5 is classified as very restrictive [1]. Therefore, variations in compressive strengths are not very restrictive but probably "normal" for concrete constructions at that time.

Structural damages

Field inspection in 1989

In 1989 Trondheim municipality (the owner of Elgeseter bridge) carried out field inspections of several concrete bridges in Trondheim, including Elgeseter bridge, with the aim to find out actual condition and repair needs Sørum [2]. From the report the following can be quoted:

"*The expansion joint was repaired in 1985 with epoxy concrete but is today (1989) damaged with consequence of ingress of water to the abutment and the shaft bearings supporting the beams. Moreover the expansion joint is at "the end of life time" (supposing that the width of the joint is close to be zero). Some few cracks are observed in beams and road plate. In two columns rust and concrete scaling are observed. Numerous "shrinkage cracks" are observed on upstream faces of columns. Due to movement of Southern abutment up to 10 mm wide cracks occur in walls and roof".*

Generally the bridge was in good condition. However, repair work should be carried out within 5 years. Cost of rehabilitation of columns, girders and beams was calculated to be 6.8 mill. NOK.

Field inspections in 1990

Because ASR was recently under investigation as a concrete problem in Norway the road authority responsible for maintenance and function of the bridge ordered an assessment of ASR as the possible cause of damage. Therefore, a field investigation was carried out in 1990, Jensen [3, 4]. The following observations were reported:

Map cracking significant of ASR occur on Southern faces of several columns and the western girder. Long vertical cracks occur in all of the columns, some with crack width up to 1.1 mm. The cracks occur mostly on western faces of columns. Some cracks can be followed from ground level up to the beams (more or less continuous 10 meter). Vertical cracks occurring in beams probably are caused by mechanical *movement of the bridge. Inspection of the northern expansion joint revealed that the width some places was less than 1 cm.*

The movement of the bridge and reduction of the expansion joint originally 20 cm but now less than 1 cm was suggesed to be caused by one of the following processes or combination of both.

- ASR had caused expansion of the beams and the road plate. The expansion of the 200 m long beams/plate should then be 0.01% after 40 years.
- Land slide of abutments had reduced the expansion joint

The field investigation suggested that ASR could be the reason for observed cracking of the bridge and core samples were taken for laboratory investigations for further documentation

Laboratory investigations 1990 and 1991
Three cores with diameter 10 cm and length 30-40 cm were taken in the following structural elements: core 1 in columns no. 2 in axe 9, core 2 in column 3 in axe 9 and core 3 in the western face of a girder at the gangway and about 3 m from the Eastern abutment.
The micro structural analysis was carried out on fluorescence impregnated thin sections and fluorescence impregnated polished slabs: Some of the results are given in table 3 [4]:

Table 3:Results from micro structural analyses

	Columns		**Girder**
	Core 1	*Core 2*	*Core 3*
Cement type	Portland fine	Portland fine	Portland fine
Water/cement - relation	0.35-0.40	0.35	0.50
Air (volume %/concrete)	3.1	2.6	1.9
Air void < 0.4 mm (air entrained)	yes	yes	no
ASR reaction products	yes	yes	yes
Reaction type*	Deleterious	Deleterious	Deleterious
% Cracked aggregates > 4 mm*	29	25	41
Cracks in paste (cracks/cm^2)*	0,08	0,04	0,25

* method by Jensen [3]

White gel precipitations in air voids and cracks, dark rims around coarse aggregates and cracked aggregates were observed in all the cores, observations which suggest occurrence of ASR. The laboratory investigation revealed that deleterious ASR occurred in all the cores. Therefore, it is most likely that ASR causes the observed cracking and expansions. Figure 6 shows reaction products in an air void and cracks in the cement paste (thin sections).

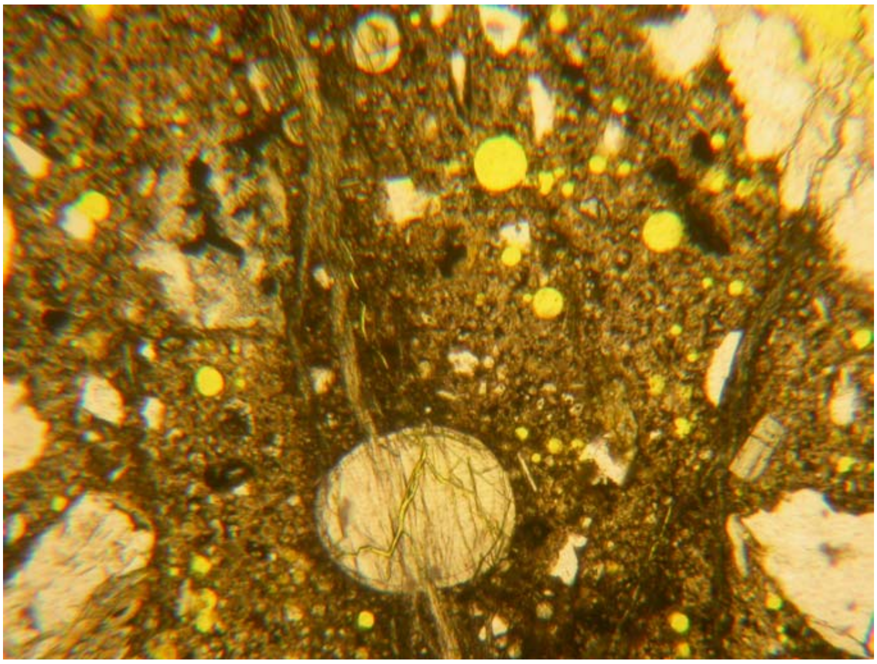

Figure 6: gel precipitation in an air void and cracks and occurrence of many small air voids (yellow) in the cement paste. Plane polarized light. Length of photo is 2 mm.

The micro structural analyses revealed the following reactive and reacted rock types:

- Sandstone and greywacke
- Mylonite
- Phyllite
- Gneiss (fine grained)

Figure 7 shows micro texture of mylonite where the precursor rock is probably sandstone. Only feldspar has survived the process of cataclasis.

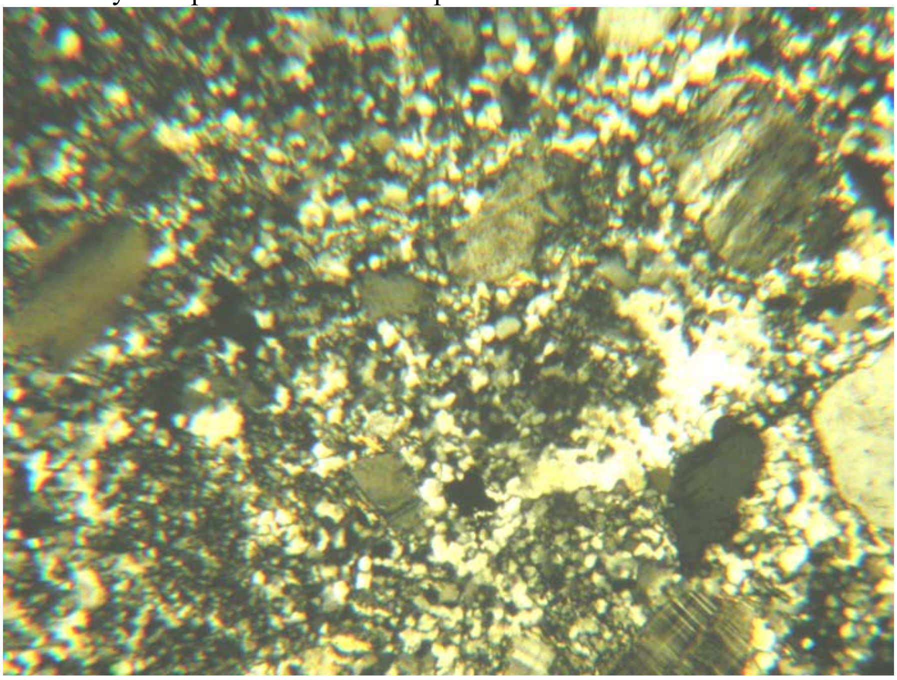

Figure 7: micro texture of mylonite photographed in polarizing light. Length of photo is 2 mm.

Table 3 includes results from a classification system by Jensen [3], namely "% cracked aggregates" and "cracks in paste". The results are obtained by counting aggregates containing cracks and aggregates where cracks runs into the cement paste (significant for ASR) as well as number of cracks in the cement paste. This on fluorescent impregnated polished half cores sawed along the length axe and observed in UV-light.

Figure 8 shows fluorescent impregnated polished half cores photographed in UV light.

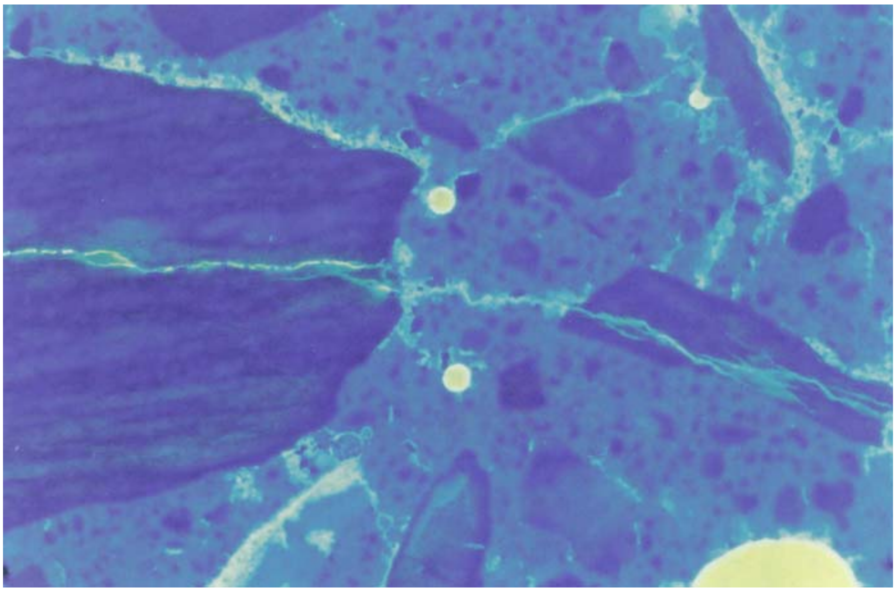

Figure 8: fluorescence impregnated concrete in UV light. Cracks occur in aggregates and in the paste

Jensen1993 [3] also made a classification system for damage in structures. The system was carried out on 468 concrete structures in Southern Norway and results were processed into a database. Elgeseter bridge was part of this investigation and was classified as type 8. According to the classification system maximum crack width should be larger than 1 mm and cracks due to ASR are observed in more than 30 % of structural elements (e.g. all the columns contain long vertical cracks caused by ASR with max. crack width 1.1 mm, and some with map cracking).

Figure 9 shows % cracked aggregates in cores related to maximum crack width in structure [3]. The plot is based on 83 cores from structures in Southern Norway. The cores were ranked as "deleterious ASR", 52 cores, "minor reaction", 7 cores, and "ASR not observed", 24 cores. ASR was documented by examination of 112 thin sections. Elgeseter bridge is shown with blue squares in figure 9.

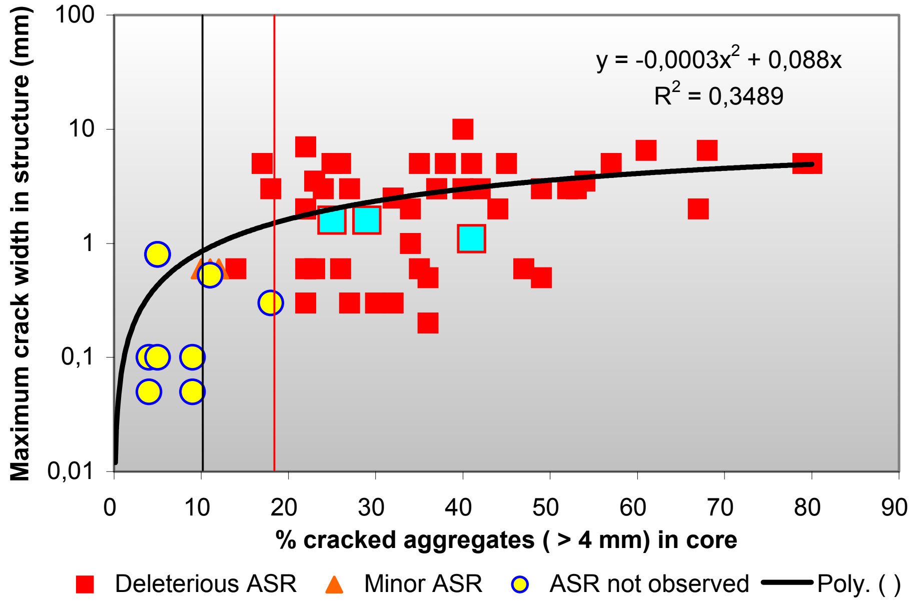

Figure 9:% cracked aggregates in cores related to maximum crack width in the structure. Results from Elgeseter bridge are shown as blue squares.

Figure 9 is a plot of cracks in structures and cracks in cores. Because of the uncertainties (counting in cores and measurements of maximum crack width in structure) the correlation is rather low but real. Moreover, a “gray zone area” between 10% and 18 % cracked aggregates (see figure 9) exists where “deleterious ASR”, minor ASR and “ASR not observed” plot together. From this investigation it can be suggested that less than 10% “cracked” aggregates is the limit to distinguish between concretes suffering from ASR or not.

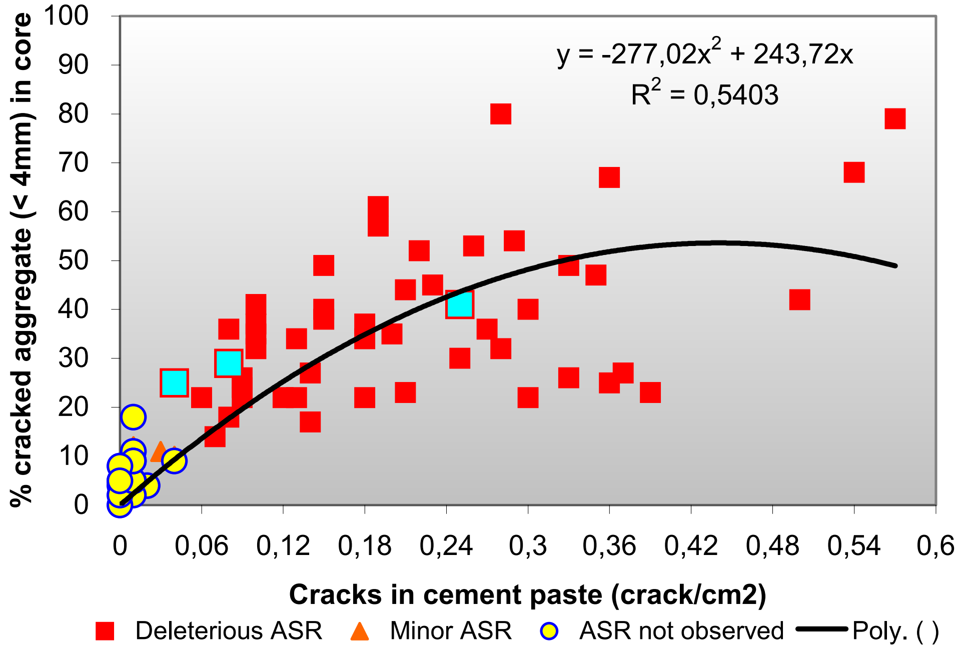

Figure 10: % cracked aggregates and cracks in cement paste in cores. Results from Elgeseter bridge are shown as blue squares.

Figure 10 shows % cracked aggregates and cracks in cement paste from the same 83 cores. Results from Elgeseter bridge are marked with blue squares. The figure shows an acceptable correlation between "% cracked aggregates" and "cracks in paste". Therefore, it is likely that ASR has caused most of the cracks occurring in the paste. Very few cracks occur in samples where ASR not has been diagnosed.

In-situ measurements

In 1995 an in-situ system for measurement of relative humidity in concrete and expansion of cracks was developed and pilot tested on Elgeseter bridge, Jensen & Haugen [5]. Eight measurement sites were mounted in one beam and 4 columns with diameter 80 cm. The concept of the system was use of inexpensive equipment and simple and systematic procedures whereby the owners of structures carried out all the measurements themselves. Relative humidity is indirectly measured by use of wooden sticks (*Gonystylus Macrophyllum*) in equilibrium with the relative humidity in the concrete, Wood [6], AEC [7], Apneseth & Hay [8], NORDTEST [9].

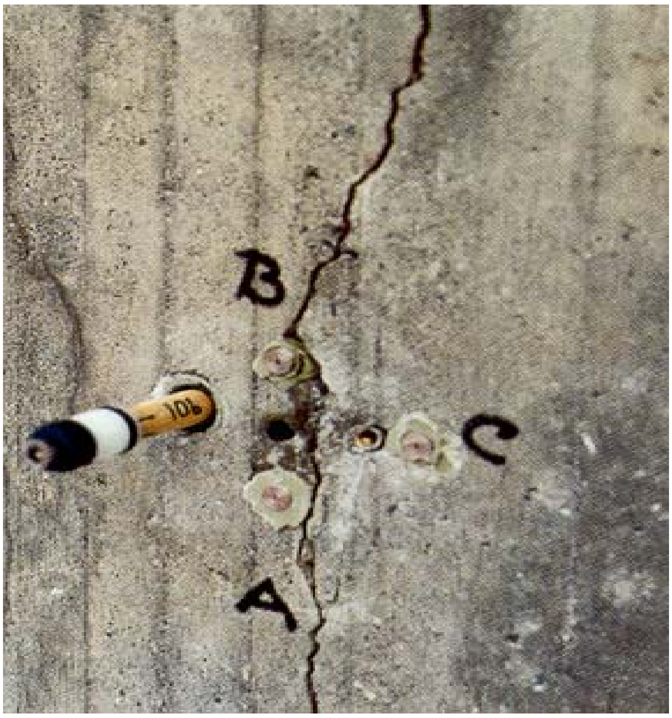

Fig. 11: location for expansion and humidity measurements, Elgeseter bridge.

For each wooden stick, calibration curves for relative humidity and water percent (electrical conductivity) of adsorption and desorption are made. Experience has shown that calibration curves vary between wooden sticks, sometimes significantly, therefore there are individual curves for each stick.
Expansion of cracks is measured by use of 3 triangular arranged rosettes (A, B, C) with an equal distances on 50 mm. Measurements are manually measured by a strain gauge (Demec gauge). Figure 10 shows measurement location with rosettes and wooden stick pulled out of the plastic tube. Figure 13 shows expansion results from location 3 in a column.
Figure 12 shows location 8 where relative humidity has been measured since 1995. After 1700 days silane type C was applied the columns, Jensen [10]. Note that the relative humidity 5 cm from the surface hereafter reduces and that relative humidity is not influenced by temperature fluctuations.

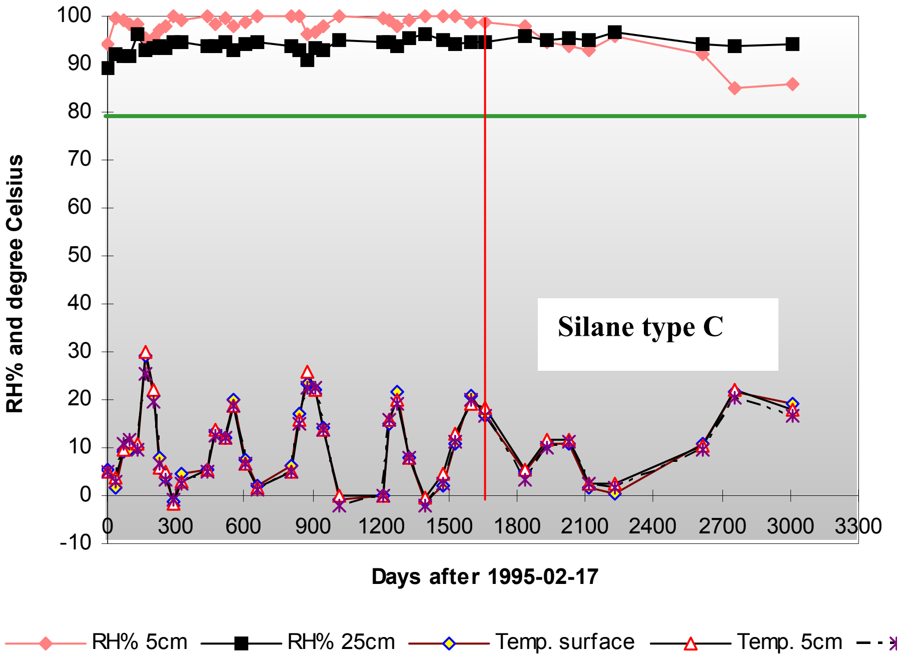

Figure 12: measurement of relative humidity and temperature at location 8. After 1700 days silane type C was applied the concrete (vertical line)

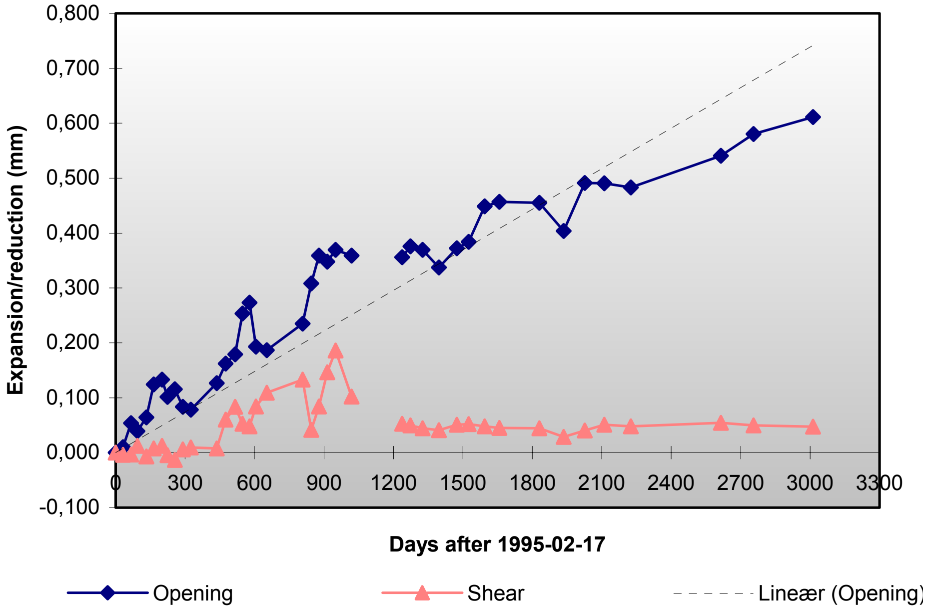

Figure 13: measurement of expansion of crack, location 3

Measurements have shown that relative humidity in the concrete varies from 100% to 87% (before impregnation with silanes). Moreover profiles have shown that the relative humidity is significantly higher on western faces relative to eastern faces of columns. Expansion of cracks varies from 0.04 mm to 0.15 mm yearly. Expansion results suggest that the rate is reduced the last few years.

Measurements have now been carried out for more than seven years and the reliability of the methods has been documented. Moreover the wooden stick method has been correlated with other commercial humidity sensors with good results, Jensen [10, 12]. In 1999 and 2000 new measurement sites were mounted on Elgeseter bridge and 3 columns were impregnated with 3 different types of silane.

Post doctoral project 1998 and 1999

A survey with aims to map the crack pattern in all the columns of Elgeseter bridge as well as tests with 3 mono silane types were carried out as part of a post doctoral project in corporation with the Road Directorate [10].

Survey of cracks in columns

A survey was carried out in 1999 with aims to register cracks in all the columns of Elgeseter bridge located in the river bank and in the river,. Crack widths (W) were measured 80 cm over the steel protection cap by use of a crack gauge and the circumference of columns (C) by use of tape measure. Results have given important information on crack widths, number of cracks in columns and distribution of cracks. Results show that crack widths vary from 0.05 mm to 3 mm and number of cracks in columns varies from 5 to 19. Largest cracks occur on western faces of columns. Measurements also were used for estimating expansion of columns [10, 12].

Figure 14 shows crack distribution in column 1 in axe 2 as a “bird eye view”.

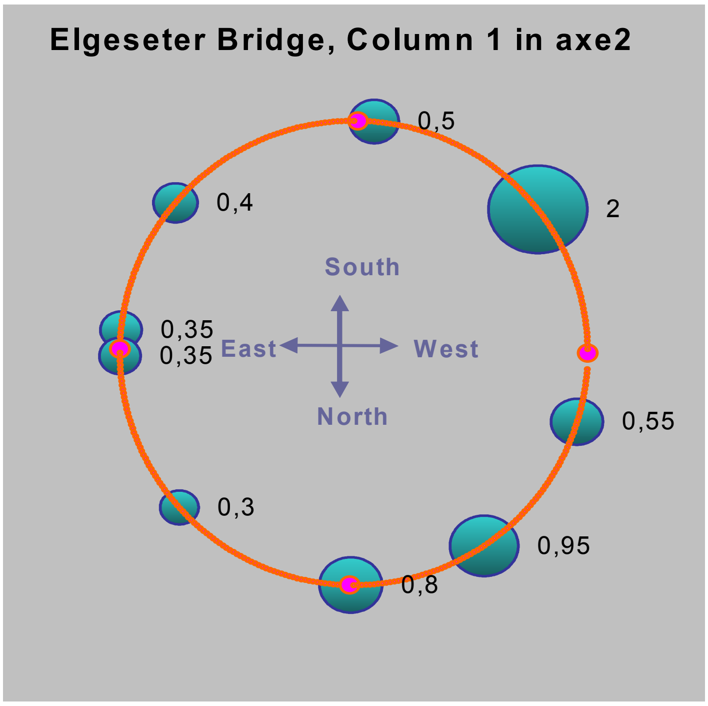

Figure 14: crack distribution in column 1 in axe 2. Filled circles are individual cracks with different sizes and number is crack width in mm. Bird eye view.

Expansion was calculated by the following equation:

(1) $W/(C - W) \times 100$ (in %)

Sum of crack width = (W); circumference of columns = (C)

Figure 15 shows expansion from all the columns in Elgeseter bridge. Note that the highest expansions occur in columns located most westerly (column 1) and in the middle of the river.

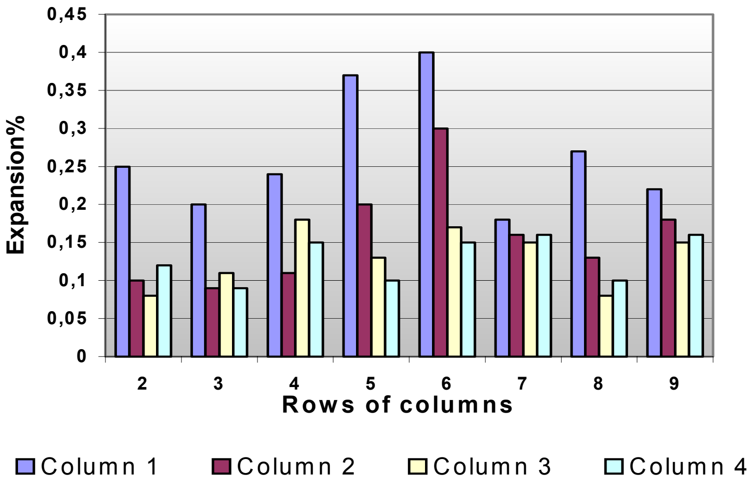

Figure 15: distribution of expansions in columns, Elgeseter bridge

Tests with mono silane impregnation

In order to measure the effect of mono silane impregnation on ASR (indirectly the relative humidity and expansion of crack) eleven new measurement locations were mounted in 1999, both on land and in the river [10]. Three different types of silanes were applied on 3 whole columns. Silane type B a liquid (*40% organosilan ester in isopropanol*) and silane type C with creamy consistency (*80% not specified silane type*) were applied by the product dealers in September 1999. Silane type A a liquid (*100% isobutyl-tri-ethoxysilan*) was applied by the Road Directorate in July 2000. All the products were applied according to the producer's recommendations.

Figures 16, 17 and 18 show the variation of relative humidity through the center of columns before silane impregnation (untreated) to latest measurements in May 2003, Jensen [13].

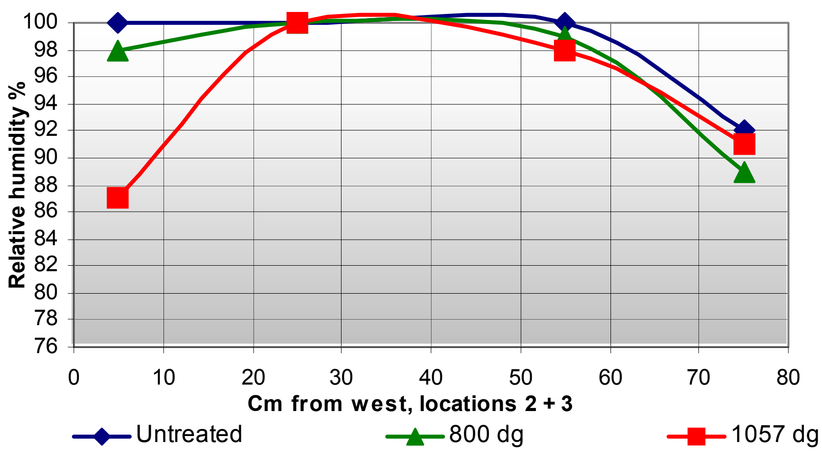

Figure 16: humidity profiles through column 1 axe 2 about 1.5 m over ground level. Measurement before impregnation (untreated), 800 days and 1057 days respectively after silane A was applied.

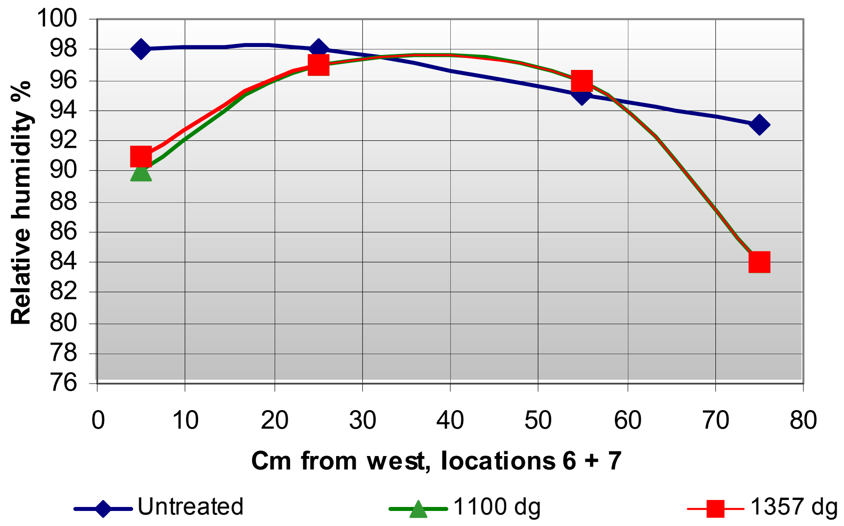

Figure 17: humidity profiles through column 1 axe 9 about 1.5 m over ground level measurements before impregnation (untreated), 1100 days and 1357 days respectively after silane B was applied.

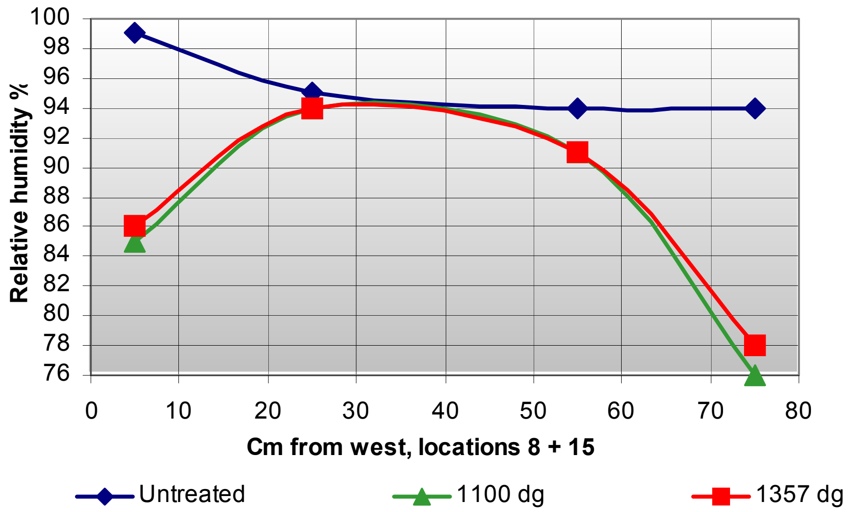

Figure 18: humidity profiles through column 3 axe 9 about 1.5 m over ground level. Measurement before impregnation (untreated), 1100 days and 1357 days respectively after silane C was applied.

In all silane impregnated columns relative humidity has been reduced significant 5 cm from the surface. In the "center" of the column impregnated with silane type C (55 cm from Western face) relative humidity has been slightly reduced. Only time will confirm if the relative humidity also reduces in the middle of the columns.

Repair

Due to the reduction of the expansion joint to near zero in 2003 rehabilitation of the bridge is urgent. It is possibly that expansion of the road plate and beams due to ASR has caused the reduction of the expansion joint, but landslide of the abutments could be another explanation. Where expansion of the road plate and beams is caused by ASR only, the road plate and beams should have expanded about 20 cm or 0.01% in

52 years. Moreover, because columns are fastened to the beams the upper part of the most northern of the columns have moved to the north (possible 15 – 18 cm) and are not vertical today. Where columns are inclined the bearing capacity of the bridge is reduced.

In 2003 the Road Directorate rehabilitated all the northern columns in axe 7, 8 and 9 on Elgeseter bridge. The author has not been involved in this work or the decision behind it. Therefore, the rehabilitation work only is briefly described in the following.

The major repair work was to move columns back to a vertical position. A special steel construction was made to support the beam before demolishing the upper 1 meter of the column by “micro blasting”, a Danish technique. Hereafter the reinforcement was cut and the column moved back to vertical position. Reinforcement was then welded to the beam and the upper part of the column remolded with concrete.

Because the rehabilitation work caused some esthetical damages to the columns (and to “hide” cracks) an elastic cement latex surface protection product was applied all rehabilitated columns. Unfortunately the two columns impregnated with silane type B and C were surface protected too. However, measurement of relative humidity and expansion of cracks is planned to continue and will include two new columns applied elastic cement latex..

Figure 19 shows the upper part of column 3 in axe 7 where the concrete has been removed. Note that reinforcement is bent due to impact from the explosion, Jensen [14].

Figure 19: upper part of column 3 in axe 7 where the concrete has been removed.

Summary and discussion

Elgeseter bridge built in 1949 – 1951 with the slender construction elements was at that time a technological and constructive challenge for the engineers. The requirement of uniform and high concrete strength required a quality and control system, which was not common at that time. A rather large testing program was performed to find the best aggregate type, aggregate combination, cement type and optimal concrete proportions.

Materials

It is interesting that marine aggregates were not used due to the risk of reinforcement corrosion (not known to occur in concrete in 1949) and air void entrainment was added to reduce the risk of frost damage. To obtain the most optimal compressive strength a special cement type was produced for the construction of Elgeseter bridge. Most of the compressive strength values from control specimens gave satisfactory results except for a short period in the summer 1950 where results were significantly low and did not fulfill the requirement of the Norwegian standard. The average variation coefficients of compressive strengths vary from 12.3% to 16.2% (ex. 4 foundations) which is not especially low, but probably "normal" at that time.

Field inspections

Field inspections in 1989 and 1990 revealed that the only expansion joint in the bridge plate originally 20 cm was reduced to less than 1 cm in 1990. The crack pattern in the bridge suggested that ASR was a possible explanation for the observed expansions and cracking of concrete. In 1990 ASR was under investigation as a possible common concrete problem in Norway and Elgeseter bridge became part of this investigation (doctoral project).

Laboratory investigations

Micro structural investigations documented the occurrence of deleterious ASR in concretes from columns and a girder. The reaction is caused by different rock types such as sandstone, greywacke, mylonite, phyllite and fine grained gneiss.

Correlations of cracks in cores and structures (field) were carried out on samples from Elgeseter bridge and other structures from the doctoral project. The parameter "% cracked" aggregates > 4 mm in cores reveals an expected low correlation with cracks in structures. However, 10% cracked aggregates > 4 mm in reacted concrete can be suggested as a limiting value to distinguish between concretes suffering from ASR and not. In all the concretes with more than 20% cracked aggregates > 4 mm deleterious ASR was identified. A more acceptable correlation exists between % cracked aggregates and cracks in the cement paste suggesting that ASR has caused the cracking in the cement paste. It can be suggested that 0.04 cracks/cm^2 is a reasonable limiting value to distinguish between concretes suffering from ASR and not.

The micro structural analyses also revealed many small air voids (<0.4 mm) suggesting the concrete to be frost resistant. This has also been confirmed after more than 50 years service life. In columns the water/cement – ratios were measured to be 0.35 – 0.40 which is in agreement with the concrete mix receipt.

In-situ measurements

It is generally accepted that relative humidity is a good measure for assessment of concrete's sensibility for ASR. A limit on 80% relative humidity in the concrete has been suggested from rather few experimental works in the laboratory and on concrete structures, Nilsson [15, 16], Stark [17], Lenzner & Ludvig [18]. Where the relative humidity is higher than 80% ASR might occur when the concrete mix is reactive and sufficient time has passed since construction period.

In 1995 an in-situ system for measurement of relative humidity in concrete and expansion of cracks was developed and pilot tested on Elgeseter bridge. Relative humidity is indirectly measured by use of wooden sticks (*Gonystylus Macrophyllum*) in equilibrium with the humidity in the concrete.

Results and correlation tests have shown that wooden sticks are reliable after 7 years continuous use. Moreover the wooden stick method has been correlated with other commercial humidity sensors with good results, Jensen [12, 19, 20]. In Elgeseter bridge the relative humidity varies from 100% to 87% (before impregnation with silanes). Moreover, profiles have shown that the relative humidity is significant higher on western faces exposed to rain water relative to eastern faces of columns which mostly stay dry when it rains. Rainwater is therefore suggested to be the most important source of water in outdoor exposed concrete structures under Norwegian climatic conditions. The wooden stick method has also given valuable information on the long time behavior of relative humidity in other Norwegian concrete structures, Jensen[21, 22, 23].
Expansion of cracks in Elgeseter bridge varies from 0.04 mm to 0.15 mm yearly. Expansion results suggest that the rate is reduced the last few years.

Survey of crack distribution in column, post doctoral project
In 1999 a survey was carried in order to register distribution of cracks and crack widths in all the columns of Elgeseter bridge. Results show that crack widths vary from 0.05 mm to 3 mm and number of cracks in columns varies from 5 to 19. Largest cracks occur on western faces of columns. Estimations of crack expansions in columns showed highest expansions in columns located most westerly (column 1) and in the middle of the river.

Tests with mono silanes, post doctoral project
Surface protection as a measure to reduce the concrete’s humidity is today insufficiently investigated and sparely reported in the literature. This is despite the fact that humidity is the most important parameter for the durability and repair of damaged structures with AAR and other deterioration processes.
In order to measure the effect of mono silane impregnation on ASR (indirectly the relative humidity and expansion of crack) three different types of silanes were applied on 3 whole columns in 1999 and 2000 [10]. Results suggest that impregnation with mono silane reduces the concrete’s relative humidity 5 cm from the surface even the columns are massive and ASR occurs in an advanced stage. Moreover, creamy consistency mono silane reduces the relative humidity more efficiently compared with the other tested products, Jensen [24, 25, 26]. Measurements of crack widths have also been carried out but the results are difficult to interpret. However, it looks like expansion of cracks has been reduced compared to earlier measurements [12].
Time will show if the relative humidity in the middle of columns will decrease too, hopefully to an innocuous level around 80%. The average annual relative humidity in the atmosphere is 79 - 80% in Trondheim. It is suggested that this is the lowest possible relative humidity to be obtained by use of surface protection in the Trondheim area.

Repair
Due to the reduction of the only expansion joint to near zero in 2003, rehabilitation of the bridge is urgent. In 2003 the Road Directorate rehabilitated all the northern columns in axe 7, 8 and 9 in Elgeseter bridge. The major repair work was to move columns back to a vertical position. Because the rehabilitation work caused some esthetical damage to the columns (and to “hide” cracks) an elastic cement latex surface

protection product was applied to all rehabilitated columns. Unfortunately the two columns impregnated with silane type B and C were surface protected, too. However, measurement of relative humidity and expansion of cracks is planned to continue and include two new columns with applied elastic cement latex.

Concluding remarks
Elgeseter bridge probably is the most thoroughly investigated concrete structure damaged by ASR in Norway. The design with slender structural elements was a technological challenge for the engineers in the 1950s and a comprehensive testing program of materials and concrete mix proportions was carried out. Based on test results durable concretes were designed and used for concreting Elgeseter bridge. However, ASR was not a known concrete problem in the 1950s. Therefore, precautions against ASR were not taken. In the 1980th significant reductions of the only expansion joint and cracking of structural elements were registered. In the early 1990s, deleterious ASR was documented and gave hereby an explanation for observed reduction of the joint and cracking of concrete.
Measurements of relative humidity with wooden sticks have given important information on the variations of humidity in structural elements which vary from 100% to 87% (before impregnation with silanes). Profiles through columns have shown that the relative humidity is significant higher on western faces exposed to rain water relative to eastern faces of columns, and rainwater is therefore suggested to be the most important source of water in the concrete. Measurements of crack widths have shown that cracks expand with maximum expansion rate of 0.15 mm per year but the expansion rate probably has decreased the last few years.
Tests with mono silane have given very promising results. One of the tested products has reduced the relative humidity 5 cm from the surface to less than 80%. Theoretical ASR should then be eliminated or significantly reduced. Unfortunately the columns with mono silane type B and C were covered with elastic cement latex in 2003 and an eventual further decrease of relative humidity due to mono silanes B and C (e.g. in the center of columns) cannot be documented.

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