ALKALI-SILICA REACTIONS IN DAMAGED CONCRETE
Static and dynamic tests
Material investigations

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ABSTRACT
The purpose of this investigation was to link observations in the field, results found in the laboratory and results from earlier investigations concerning the effects of frost and ASR on the static and dynamic strengths of structural members. The Road Directorate decided to carry out laboratory tests on a damaged bridge deck, and in June 1993 four concrete beams were cut out from the deck of a road bridge, constructed in 1977. The investigations were carried out in close cooperation between the Road Directorate and the Civil Engineering Department of the Danish Engineering Academy, Physics and Materials Science Section. The structure showed severe damage due to frost and ASR, and it was therefore decided to demolish the bridge deck and reconstruct it in 1993.
The project comprised the following tests:

- Evaluation of earlier investigations of the bridge deck
- Dynamic and static laboratory tests in bending on large structural beams
- Compressive strengths of cores
- Evaluation of the AS-reactivity of the aggregate
- Evaluation of the influence of ASR on watersorption
- Evaluation of damage - thin sections and polished sections

Keywords: Alkali-silica reactions, beam, bridge,cracking, durability, dynamics, frost, reinforced concrete, strength, test.

INTRODUCTION
In 1984 - 1989 the Ministry of Transportation, (the Road Directorate) carried out research and examinations of reinforced concrete beams with alkali-susceptible aggregates (Ministry of Transp. 1990). Axial sections on cores and thin sections has been one of the methods for assessing the condition of a structure. However, it is difficult from laboratory research alone to estimate the extent to which damage implies loss of load- carrying capacity. In order to link results in the laboratory and the theory of structural design, the Road Directorate decided to carry out investigations on damaged reinforced concrete beams from a structural member damaged by ASR (Ministry of Transp. Rp. 12, 1994).

BACKGROUND

This paper describes some of the static and dynamic tests and materials research, which have been carried out on a bridge deck from a bridge owned by the Road Directorate. The bridge deck was demolished and reconstructed in the summer of 1993.The abutments were repaired with in-situ cast concrete.

BRIDGE DESIGN

The bridge was built on 8 July 1977 ($42m^3$ concrete) as an in-situ cast single-span two-hinged frame-tunnel, and founded on solid bottom with compressive reinforcement between the frame foundations. Data for the reinforced concrete - see table 1. Vacuum-dewatered concrete was cast on the bridge deck. The test beams used in the investigation were cut out of the bridge deck with a watercooled diamond saw.

Table 1. Bridge-deck concrete.

Specifications $[kg/m^3]$	**Compression strength** σ_{ck} **= 30 MPa**
Cement PC(A/L/S)	340
Water (V/C $\leq$ 0.55)	128
Fine agg. 0-8mm (alkali-susceptible)	710
Coarse agg. 8-32mm (non-susceptible)	1106
Aerocon & Sparcoplast	36 ml / m^3 & 360 ml / m^3
Reinforcement is Tentorsteel $\sigma_{yk} \geq$ 560MPa and mild steel $\sigma_{yk} \geq$ 240MPa.	

MATERIAL TESTS AND RESULTS

In this paper only some of the measured material properties will be presented.

COMPRESSIVE STRENGTH

At a given maturity, a lower strength can be expected for drilled cores than for normally cast cylinders. The relation between drilled cores and cast cylinders can be seen in table 2.

Table 2. Results from compression tests 1977 and 1993.

Date	Type	Strength [MPa]	Correction	Strength $\sigma_{c,k}$ [MPa]
July 1977	cast	31.5	0.8	25.2
Sept. 1977	drilled	23.7	1.0	23.7
Nov. 1993	drilled	21.2[1]	1.0	21.2
[1] 8 drilled cylinders, 2 test results were cancelled. Empirical deviation = 2.7 MPa				

$$\sigma_{c,cast} = \mathbf{1.25} \cdot \sigma_{c,drilled} \Rightarrow \sigma_{c,drilled} = \mathbf{0.8} \cdot \sigma_{c,cast}$$

Sorption properties of concrete

Deleterious ASR in concrete occurs when alkali-ions from the cement dissolve in water and produce alkalihydroxyl, which reacts with alkali-silica-reactive aggregate. The result can be alkali-silica-gel, which can absorb very large quantities of water. The absorbed water can expand and produce cracks in the concrete. According to (Anders Nielsen 1993) the chemical reaction will have two effects. The amount of evaporable water will be reduced as the ASR-gel contains some non-evaporable water. The ASR-gel will contribute to the hygroscopic binding capacity of the concrete, and therefore the watersorption curve will be higher than that for a concrete without ASR-gel. The results show that the investigated concrete contains ASR-gel, because the watersorption curve is on a higher level than that of the reference concrete. Chemical shrinkage

Chemical shrinkage was measured on reused sand (0-4mm) from acid-treated concrete specimens. A mean value of 0.37ml dissolved silica/kg sand showed that more unreacted alkali-silica exists. Therefore the concrete has the potential for further reactions and expansions. This agrees with observations in thin sections, where unreacted aggregates without cracks were observed; thin sections from 1985 compared with thin sections from 1993 showed that the increase of alkali-silica reactions has been low, possibly because the alkali-ions from the cement have been used up. New reactions can be started by adding alkali-ions; as an example it can be mentioned that NaCl is used in large amounts for deicing in Denmark

STATIC TESTS AND RESULTS

A sketch of the reinforcement in the test beams is shown in figure 1.

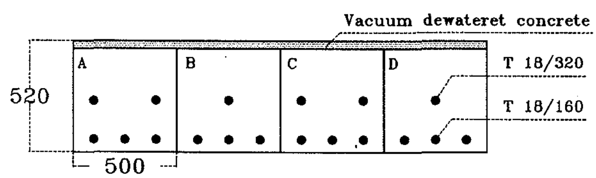

Figure 1. The reinforcement in the cross-section of the testbeams (mm)

The calculated moments at failure ($M_{v,calculated}$) for the test beams: (A: 319kNm, B: 262kNm, C: 223kNm & D: 210kNm). The moments differ due to different areas of reinforcement (A_s) and effective heights (h_{eff}). In the tests an estimated value of the failure-moment M_u = 220kNm was used, and the calculated failure-load ($P_{failure}$) excludes dead-load (P_g = 6.2kN/m), as $P_{failure}$ is the load on the beam at failure.

Test set-up and results

Figure 2 show the set-up used in the static- and the dynamic tests and the arrangement of measuring equipment. The beams were tested in 10 steps and for each load-level (10%, 20%... of estimated failure-load) the load, deformations, bending and cracks were measured.

The following measurements were made (at approx. ½ hour intervals):

- Load measured with tension and compression cells (25ts-Eilersen)
- Deflections measured with three dial-gauges (0.01 mm)

- Longitudinal deformations at the top and bottom of the beams with Demec mechanical strain gauge (Instr. nr. 482; accuracy ± $3\cdot10^{-6}$, $1\cdot10^{-5}$ strain is one division)
- Observation and registration of cracks with a crack-gauge (0.05 mm)
- Photogrammetric measurement of deflections and strain (sensitivity approx. 0.5 mm)

Measured and calculated parameters:

1. Crack-width: w [mm]
2. Strain:
   $\varepsilon = (l_n + l_{n+1})\cdot 1\cdot 10^{-5}$, where l_n and l_{n+1} are measurings at the n'te load level and the (n+1)'te load level respectively

The results of the strain-measurement will not be shown in this paper.

3. Curvature κ [mm^{-1}]
4. Bending u [mm]

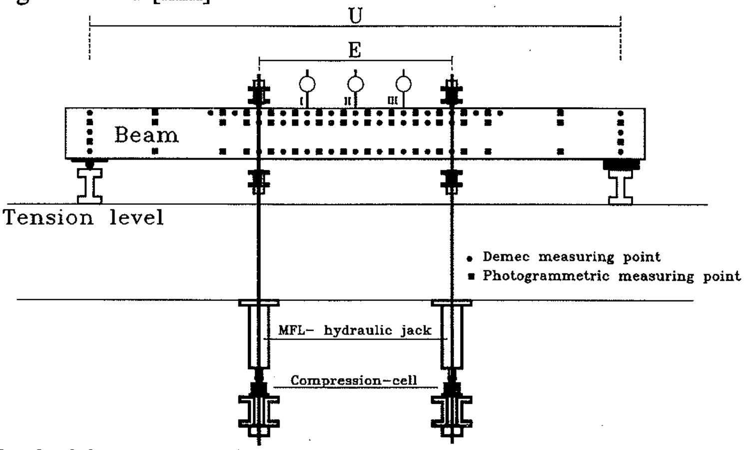

Figure 2. Sketch of the test rig for dynamic/static tests and measuring points on beam. U= 4800mm (A & B); U= 5460mm (C & D); E = 2000mm (A, B, C & D)

ad. 1& 3 Crack-width and Curvatures

Table 3 shows corresponding values of calculated and measured crack-widths for beams A and B. The curvatures (5/) κ [mm^{-1}] of a beam can be calculated, and the curvature (κ) is used for the calculation of the bending (u):

$$\kappa = 1/R = \sigma_s /[E_{sk} (h_{eff} - h_c)] \quad \& \quad u = 1/10 \cdot \kappa \cdot l^2 \text{, where}$$

σ_s	Tensile stress in the reinforcement [MPa]
E_{sk}	Modulus of elasticity of the reinforcement [MPa]
h_{eff}	Effective height of the cross-section of the beam
h_c	Height of the compression-zone [mm]
l	Span of the beam [mm]

There is fairly good agreement between the calculated (DS411) and the measured crack widths but some divergence on the curvatures. In general all the measurements are conservative compared to the calculated results.

Ad. 4. Bending u[mm]

Table 4 shows the calculated and measured bending for beams A and B at each load level. The results from the photogrammetric method are not presented in this paper.

Table 3. Crack-width and bending for beams A & B.

Crack-width w[mm]				Bending $\kappa \cdot 10^{-7}$ [mm]		
Level	Calcu-lated	Measured		Calcu-lated*	Measured curvature κ**, at point II.	
		Beam A	Beam B		Beam A	Beam B
1	0.11	none	none	10.8	2.3	0.9
2	0.23	none	none	21.5	3.3	2.2
3	0.34	none	< 0.05	32.3	4.1	3.3
4	0.46	none	0.10	43.1	5.9	5.7
.	.	.	.	.	.	.
9	1.02	0.10- 0.90	0.10-0.75	96.9	27.1	26.1
10	1.14	> 0.90	> 0.75	107.8	29.4	-
DS 411: $w = 5 \cdot 10^{-5} \cdot \sigma_s \cdot a_w^{-1/2}$; σ_s is tensile stress in the reinforcement and a_w is a crack parameter				κ* κ_{1-2}**	$= \sigma_s /[E_{sk}(h_{eff} - h_c)]$ $= \varepsilon_1 - \varepsilon_2 / 2 \cdot h_{1-2}$	

The agreement between calculated and measured bending (table 4) is rather good. At higher load levels the measured deflections are higher than the calculated. The photogrammetric measurement has the same order of magnitude.

Table 4. Bending of Beams A and B by different measuring methods

Bending [mm] Center-line of beams (point II).					
Load	**Calculated** $u_{max} = 1/ 10 \cdot \kappa_{max} \cdot l^2$	**"Measured curvature"** u_{max}		**Dial-gauge** u_{max}	
		A	B	A	B
1	2.49	0.54	0.21	1.01	0.81
2	4.95	1.30	0.71	1.56	1.67
3	7.44	2.25	1.48	2.09	4.24
4	9.93	3.61	2.71	2.79	5.44
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9	22.33	24.32	20.96	9.94	18.17
10	24.84	31.07	-	12.25	-

DYNAMIC TESTS AND RESULTS

Loads from traffic will reveal the dynamics of a bridge. Two tests (beams C and D) were carried out to illustrate how dynamic loads influence a damaged bridge construction. Failure from a dynamic load is also called fatigue fracture from a large number of load-oscillations (10^5 to 10^8 cycles). It is therefore important to investigate variations of stress, because oscillations of stress can cause microscopic fractures in the structure even if the stress is lower than the stress which would cause fracture at a static load. A dynamic fracture differs from a static fracture because repeated oscillations of loads give irreparable microscopic cracks in the concrete. The dynamic tests were of the following type:

- Dislocated oscillations-influence, where the max. and min. tensions have the same sign but are non-zero. The used test rig is seen in figure 4.

Loading

Because of the ASR-cracks in the test beams it was expected that a dynamic load would be critical. The first dislocated oscillations were therefore carried out at a level of 25-50 kN on each yoke at a low frequency, and continued with various levels and frequencies (table 5). The loads on the test beams correspond to the loads from lorries with a total weight of 9.000 kg, 12.000 kg and > 25.000 kg.

Development of fracture for beams C and D

The first cracks were observed after approx. 2 hours (25-50 kN). In general the cracks increased in the first few hours after changing the load and the frequency, and thereafter stabilized. When the tests were stopped many of the cracks reached the upper level of the reinforcement. Table 6 shows the dislocated oscillations used and the swings obtained compared to numbers of truckaxles of 4o kN

Table 5. Loading and numbers of oscillations for beams C and D

Load [kN]	Beam C			Beam D		
	Frequency $f_C[s^{-1}]$	Time [s]	Oscillations N_{iC}	Frequency $f_D[s^{-1}]$	Time [s]	Oscillations N_{iD}
25-50	0.041	353.280	14.532	0.118	1.200	142
25-50	0.076	160.860	12.168	0.204	600	122
25-50	0.171	166.140	28.352	0.365	86.700	31.646
25-50	0.345	869.040	299.668	0.435	7.860	3.419
25-50				0.608	514.800	312.998
38-64	0.401	173.160	69.542			
50-75	0.383	108.300	41.494			
25-50	0.383	325.260	124.621			
50-75	0.437	367.740	160.585	0.591	515.400	304.601
62-77	0.980	254.940	249.941			
75-100				0.653	621.240	405.670
	N_{iC}		**1.000.903**	N_{iD}		**1.058.598**

For a bridge deck similar to the deck in this investigation, axle-loads were registered in a traffic census. They have been recalculated to a standard axle load of 40 kN which gives an annual average 24hour-traffic of (365· 5714) = 2.085.610 "40kN-axles".

Dividing the number of oscillations ($\Sigma N_{4000\ kg}$) by the annual average 24-hour-traffic gives the following values of n for beam C and D:

n_C = 4.810.776 / 2.085.610 = 2.3 years
n_D = 13.136.188 / 2.085.610 = 6.3 years

Table 6. Load (P_i), passages (N_i), and 4000 kg axles for Beams C and D.

Load P_i [kN]	$P_{4000\ kg}$ [kN]	Beam C		Beam D	
		$N_{i,C}$	$N_{4000\ kg}$	$N_{i,D}$	$N_{4000\ kg}$
25		239.672,5	36.571	174.163,5	26.575
38		34.771	28.321		
50		340.712	831.816	326.464	797.031
62	40	124.970,5	721.331		
64		34.771	227.875		
75		101.039,5	1.248.810	355.135,5	4.389.340
77		124.970,5	1.716.052		
100				202.835	7.923.242
Σ	$*N_4 = (P_i / P_4)^4 \cdot N_i$	1.000.907	4.810.776	1.058.598	13.136.188
* Jf. AASHO, 1962 /11/.					

Neither of the two test beams were crushed at the end of the dynamic test, which means that the construction might have behaved well for a further 2-7 years of traffic. Under the circumstances for the test beam D - load from a truck on 500 mm bridge deck width - the bridge might have behaved well for 5-15 years of traffic; in this assumption climatic deterioration has not been taken into account.

DISCUSSION

The material tests covered cracks and crack development, development of strength and static/dynamic tests. Generally microcracks can be observed in concrete, and are caused by:

- Thermal stresses during curing.
- Frost action and use of deicer.
- Chemical reactions such as alkali-silica reactions
- Drying shrinkage connected with the hydration of cement.

Hence investigations of drilled cores have shown cracks parallel to the surface moving inwards concurrently with the intrusion of water and dissolved salt. This can result in differences between the compressive strength of a normally stored cylinder, a cylinder stored in a NaCl-solution and a drilled core depending on the direction of drilling. In this investigation most of the cracks were parallel to the surface and the bottom of the bridge deck, and a reduction in the compressive strength of 20-55% was therefore expected. Results from compression tests of the concrete 1977 - 1993 (table 2) do not show reductions, and therefore it cannot be concluded that ASR had any influence.

The bridge was built as a single-span two-hinged frame-tunnel and the bridge deck was fully fixed at the abutments. Loads on this system will give thrust-forces in the bridge deck and negative moment at the terminal points of the bridge deck. In the static and dynamic tests the static system was a simply supported beam; that a plate can take up a greater force than a beam was taken into account. The original construction was more capable of taking up the traffic load than the test beams indicate. Loads from heavy lorries have a greater influence on the fatigue strength than light traffic loads. In the tests it was attempted to force fatigue failure by loading the beams with a dislocated oscillation - 25-100kN and frequencies 0.971-

0.041Hz (period 1-25sec.). The max. load from a rear axle is 8 tons and the max. load from a front axle is 6 tons, which means that a 1 metre bridgedeck width can take up approx. 8 tons (two rear axles divided by two). From this point of view the chosen load levels are reasonable, but the chosen frequencies are not quite realistic. As long as the chosen frequency is not too far from the real frequency, it can be estimated that the frequency has only a slight influence on the fatigue failure, which is supported by the literature. The slower period may have caused the load to act quasi-dynamically, and the absence of shock excitation may have resulted in the test beams resisting a larger number of oscillations than they would have done in a purely dynamic test.

CONCLUDING REMARKS

The observations can be summarized as follows:

- No reinforcement corrosion was observed, the increase of ASR has been rather low since 1985 and the intrusion of chloride is less than 3 mm from the surface.
- Compression tests show that compressive strength has not been appreciably lower during the lifetime of the bridge. The deformation of the drilled cores was measured 2½-5 times larger than in non-damaged concrete.
- The observed damage is due to defects in the casting and the compacting of the concrete. These defects have resulted in damage from frost and ASR. In thin sections and impregnated polished sections there were observed:
    - A large amount of aggregate which was not surrounded with cement paste.
    - Inadequate air-entrainment and ASR-gel in cracks and pores.
    - Cracks indicating that the fresh concrete was inhomogeneous and that it must have been difficult to compact the concrete.
- In the static tests, failure occured in the test beams at the calculated level approx. 220kNm.
- In general the measured crack widths are smaller than the theoretical.
- The behaviour of the beams under static and dynamic loading was as expected.
- Neither of the two test beams were crushed at the end of the dynamic tests, which means that the construction might have behaved well for a further 2-7 years of traffic. The bridge as a whole might have behaved well for a further 5-15 years of traffic, if climatic deterioration is not taken into account.
- Static and dynamic load-carrying tests have shown that the observed damage has little influence on the load-carrying capacity of the structural members.

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