LOK and CAPO Tests

The experience of pull-out test during

The Great Belt Link (Storebælt) project in Denmark

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Concrete Technology

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1. The Great Belt Link Project

The Great Belt Fixed Link (Danish: Storebæltsforbindelsen) runs between the Danish islands of Zealand and Funen (eastern and western Denmark). The 18 km project consists of three structures: a road suspension bridge and a railway tunnel between Zealand and the small island Sprogø located in the middle of the Great Belt, and a box girder bridge for both road and rail traffic between Sprogø and Funen. The "Great Belt Bridge" (Danish: Storebæltsbroen) commonly refers to the suspension bridge, although it may also be used to mean the box-girder bridge or the link in its entirety. The suspension bridge, officially known as the East Bridge, has the world's third longest main span (1.6 km), the longest outside of Asia.

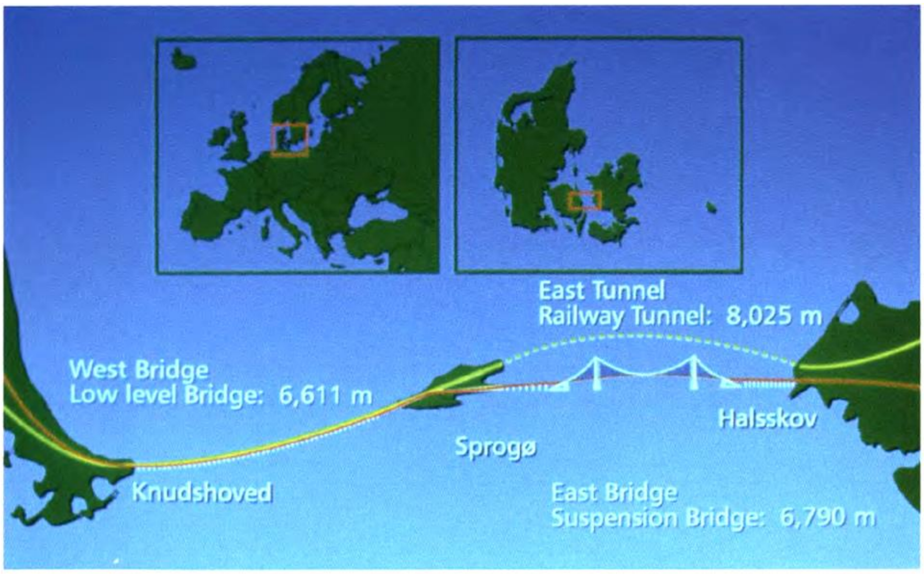

Fig. 1. The Great Belt Link.

Construction work on Storebælt took place between 1988 and 1998. During this period, thousands of engineers, craftsmen and skilled workers were engaged on the project. When construction was at its peak in the early 1990's, more than 4,000 were employed at construction sites around Storebælt.

The total construction costs for the entire Storebælt project amounted to DKK 26.5 billion at current prices. In addition to the construction costs were the interest charges, so the total debt at the opening of the bridge in 1998 was approximately DKK 36 billion [1].

Operation and maintenance are performed by A/S Storebælt under Sund & Bælt. Construction and maintenance are financed by tolls on vehicles and trains.

The fixed traffic link across Storebælt is the largest infrastructure project to be completed in Denmark in the 20th century, and it marked the completion of the Danish railway and motorway network. Thus, the domestic traffic between all major towns can flow without having to be transported by sea over the straits separating the different parts of the country.

During planning, design and construction of the Storebælt Link the environmental aspects were considered more carefully than ever before and as a result, the impact was insignificant.

The size and importance of the Storebælt Link have also implied that aspects of durability and resistance to accidental actions were studied in an unprecedented scale to keep the risk level at a minimum.

The construction of the Storebælt Link has contributed substantially to the global experience within engineering structures of the actual size, and it was therefore felt by the Management of Storebælt that these experiences should be made available for the international engineering profession [2].

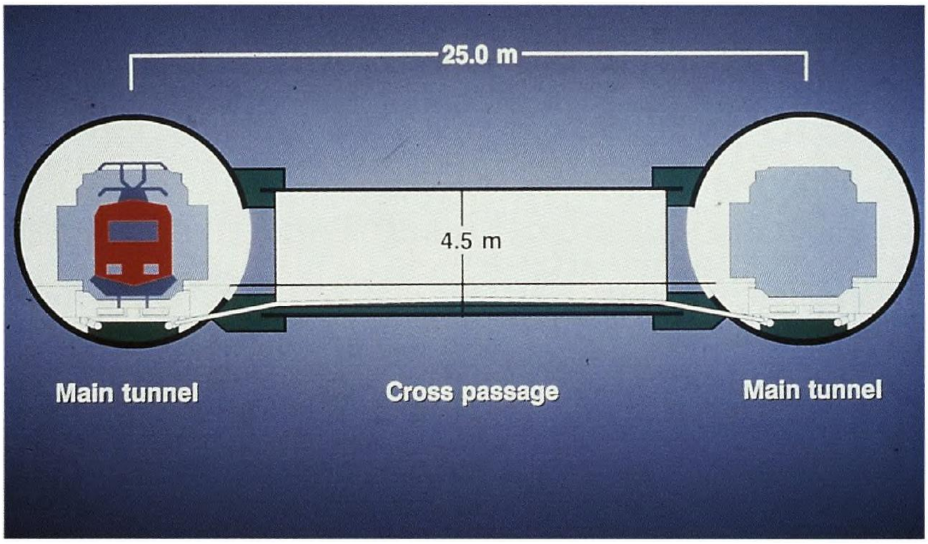

Fig. 2. Cross section of the East Tunnel.

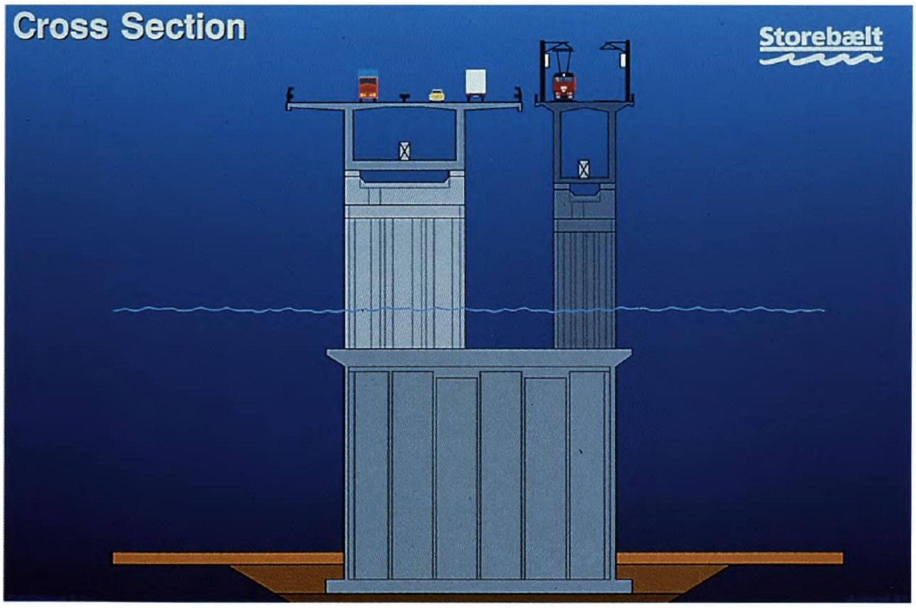

Fig. 3. Cross section of the West Bridge.

Fig. 4. Panoramic of the East Bridge.

2. Background [3]

Throughout the 1960’s and 1970’s in Denmark, many concrete structures (parking decks, balconies, swimming pools, etc.) were built without regard to durability, resulting in extensive in-depth renovations after 10-15 years of service. The problems could be traced back variously to de-icing salts, the use of additives without sufficient experience, and unsuitable aggregates (alkali-silica reactions and frost attacks), as well as to inefficient work procedures during construction.

After this experience, the conditions for concrete works were made more rigorous, and new mixes and procedures were steadily developed to improve the quality and especially the durability of concrete structures. These included lower water-cement ratios, the use of pozzolans (eg. fly ash and silica fume), plasticizers, air entrainers and improved aggregate types. Also construction methods were improved, especially focusing on the hardening process, when the concrete must be protected effectively against evaporation and wide temperature variations.

100 years' durability was selected as the key requirement for the Great Belt Link Project in order to obtain a service life longer than housing and smaller bridge projects (where 50 years' durability normally had been required) and offshore projects (25-30 years). The 100-year period was also selected as the basis for operational risk analysis, fatigue design, investigations of ice and wind forces, and for the general functionality of the bridge.

3. Overview of the use of concrete [4]

On the basis of the considerations, the SAB’s (special work descriptions) for the different parts of the project were prepared for the tendering.

The options for the East Tunnel were for it to be either bored or submerged. The chosen design was a bored tunnel with segmental concrete lining in the two main tunnels and cast iron segments in the cross-passages.

At both ends, cast in situ cut-and-cover tunnels led into the bored main tunnels. This solution included an estimated 260 000 m^3 of concrete supplemented by 75 000 m^3 of annular grout for injection behind the segments.

For the West Bridge, tenders were invited for three solutions: all-concrete, composite steel/concrete, and steel, all three including concrete piers. At the end, an alternative bid based on an all-concrete solution was accepted, resulting in an anticipated need for 500 000 m^3 of concrete.

The East Bridge tenders were based on the use of concrete for anchor blocks and approach span piers. For the pylons and the approach span girders the tenderers could choose between concrete and steel, whilst the girders for the suspension bridge were to be made of steel. The chosen combination of tenders resulted in a concrete substructure inclusive of anchor blocks and pylons, and a steel superstructure for the approach spans and the suspension bridge.

250 000 m^3 of concrete was anticipated for the East Bridge substructure, together with a small amount of grout for injection below the prefabricated caissons.

As a result, a total of 1.1 million m^3 of concrete, inclusive of grout, was planned to be required for the entire project.

East Tunnel

The East Tunnel SAB defined the requirement for three main types of concrete, two A-types and one B-type. Type A1, for segment production, was a 50 MPa concrete with a maximum water content of 135 kg/m^3 and a maximum equivalent water/cement ratio of 0.35. Type A2, for in situ castings, was a 40 MPa concrete, with requirements for water content and water/cement ratio identical to those for type A1. Type B1 was a 35 MPa concrete with a maximum water content of 140 kg/m^3 and a maximum equivalent water/cement ratio of 0.45. The specification also included requirements for the grout.

An additional concrete type, BB, with 8 mm aggregate, was developed, based on the B1 specification with increased water content. Also, a type 2A plastic concrete for precast walkway segments was developed. This had a maximum water/cement-ratio of 0.35 and a maximum water content of 140 kg/m^3, and was thus in accordance with the type B1 specification.

West Bridge

The West Bridge SAB defined the requirement for two main types of concrete, A and B, identical to East Tunnel types A2 and B1 except for a strength requirement of 45 MPa for both types. In addition, a mix type with a water content outside the type B specification (mix 200) was developed.

East Bridge substructure

The SAB for the East Bridge defined concrete types A and B identical to the West Bridge types, apart from a maximum water/cement ratio for type B of 0.40. In addition, the SAB included specifications for an under-base grout to be used below the caissons, and also allowed for the possibility that the contractor might develop a special concrete type outside the specifications for use in the anchor block massifs.

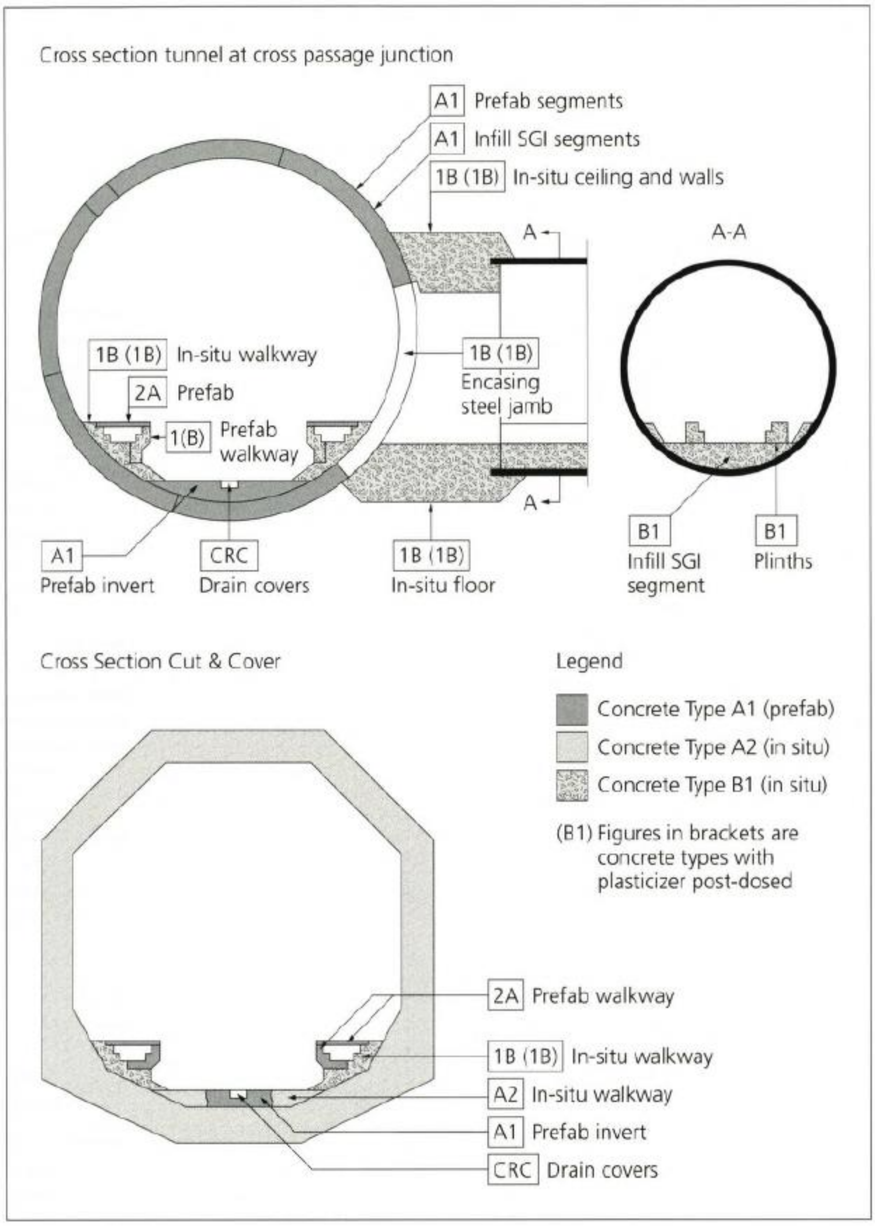

Fig. 5. Summary of the use of main concrete types in the East Tunnel. The A2 type was also used for portal buildings.

Quantities of concrete

Table 1 summarizes the concrete quantities used for permanent structures on all three principal parts of the project. The figures are approximate. The total amount of concrete is 1 100 000 m^3. In addition to these figures, all contractors used considerable extra quantities for pre-tests, for full-scale trial castings, for temporary structures, and as waste.

East Tunnel, 250 000 m^3 / 79 000 m^3		
Segment production	Types A1, 2A and 1B	175 000 m^3
In-situ Halsskov	Types A2, B1, 1B and BB	32 000 m^3
In-situ Sprogø	Types A2, B1, 1B and BB	43 000 m^3
Grout		79 000 m^3
West Bridge, 524 000 m^3		
Caissons	Types B and 200	181 000 m^3
Pier shafts	Type A and lean	92 000 m^3
Rail girders	Type B	111 000 m^3
Road girders	Type A and B	140 000 m^3
East Bridge, 269 000 m^3 / 6 000 m^3		
Approach spans	Type A, B and low heat	53 000 m^3
Anchor blocks	Type A, B and low heat	104 000 m^3
Pylons	Type A and B	112 000 m^3
Grout		6 000 m^3

Table 1. Summary of the concrete quantities used for permanent structures at all parts of the project.

4. Concrete requirements [5]

All parties involved in the different phases of a construction project have a collective responsibility for the quality of the final structures: the client setting up the overall functional requirements, the consultants designing the structures, the contractors performing the construction work, and the suppliers providing the basic materials during construction.

For a large project like the Great Belt Link, it was to be expected that many parties from many different countries would participate in the design and construction phases, each with their special background, and not all with experience of Danish concrete technology, the Danish Construction industry, and the environmental conditions for this project.

To manage this situation, Storebælt decided in September 1987 to formulate general specifications (FAB) covering the overall requirements for the concrete work and the quality management of the entire project. The FAB could then be used by all consultants involved in its different parts. The structures were to be designed for a minimum 100 years' service life, meaning that they had to maintain adequate safety and serviceability for that period of time without incurring unforeseen high maintenance and repair costs. One important objective was therefore to specify the requirements to prevent deterioration from alkali-silica reactions, frost attack, and reinforcement corrosion due to chloride ingress.

Different degrees of sophistication in protective measures could be foreseen for different structural components, depending on how easily accessible, maintainable, repairable, and replaceable they were when the structures were in service. Specific requirements (not part of the FAB) for such components were included in the special specifications, SAB.

Background and general FAB specifications

The FAB were set up by a small Danish task force chaired by Storebælt. The work involved about 30 international concrete experts in specific areas to write and review the requirements. The FAB were based on a long Danish tradition for the content of such documents and took into consideration the practical experience obtained from major Danish construction works during the last 25 years and the durability problems observed on exposed structures during the same period and from the latter concerned structures such as swimming pools, balconies, parking decks, and motorway bridges - of which the Ölands bridge in Sweden was an example of early deterioration of concrete structures.

The main objectives for the concrete in the Great Belt Link were defined as durability, strength, homogeneity, and quality assurance. In accordance with Danish methods, these formed the basis of requirements for the constituent materials, the composition, preparation, and curing of the concrete, and the testing before and during construction.

The FAB put greater emphasis than ever before in Denmark on the importance of pretesting, trial mixing, and trial casting of structures before start of construction, together with thorough planning and training. This meant that no concrete work was allowed to start before all pretesting and all planning documentation had been accepted by the client.

The required planning documentation consisted of quality plans for all types of work, including method statements, work and inspection procedures, work and inspection instructions, drawings and -where necessary- risk assessments.

0	General
1	Scaffolding and formwork
2	Mild steel reinforcement
3	Prestressing tendons
4	Concrete
4.1	General
4.2	Requirements for the constituent materials of the concrete
4.3	Composition of the concrete
4.4	Execution of the concrete work
4.5	Inspection & Testing
	General note

Fig. 6. List of FAB contents.

The FAB requirements were also intended to deliver concrete structures satisfactorily free of defects, so they addressed the microstructure, including limitation of microcracks and porosities.

Another important issue was an increased focus on achieved properties and characteristics, determined by testing the concrete in the final structure. For this reason, in-situ testing of strength and microstructure was specified. Also, strict requirements as to curing and temperature control during hardening were of major importance in the efforts to ensure durability.

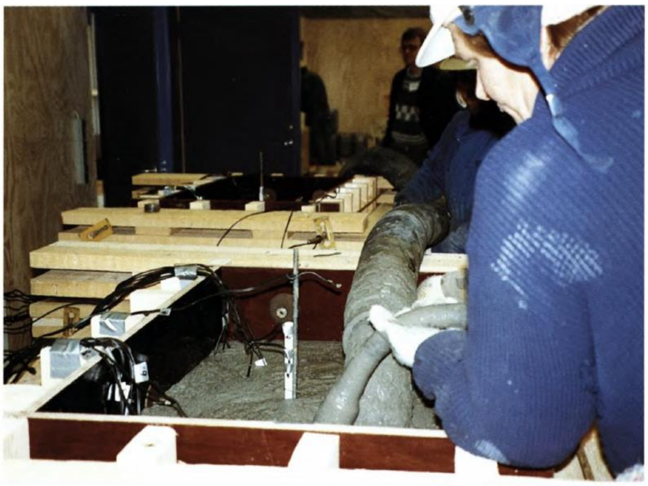

Fig. 6. Pretesting work.

Fig. 7. LOK-test for in-situ strength assessment.

Concrete strength [6]

Concrete strength is influenced by the water/cement ratio and the curing conditions, which are also important for durability. The FAB requirements for concrete strength were therefore also related to durability aspects.

This was measured on concrete cylinders (diameter 150 mm and 300 mm high) manufactured and cured in accordance with DS 423.20 and DS 423.21 respectively. The cylinders were tested in compression according to test method DS 423.23 and the result represented the potential concrete compressive strength of the concrete.

Inspection of potential compressive strength, however, gives no guarantee of safety against failure of the concrete structure, so the FAB specified that, in addition to the potential compressive strength, the achieved characteristic compressive strength should be controlled and evaluated from samples of the structure by in-situ testing of the concrete.

The FAB required that development of the concrete strength had to be determined during pretesting and trial casting. This counted for potential compressive strength and splitting tensile strength as well as the achieved compressive strength (pull-out strength) developed in the structure.

Potential concrete strength

For a given constituent material, the properties of the cementing matrix are decisive for the concrete's potential strength (cast-test specimens). During storage, test specimens should be kept stored under water at a temperature of 20 ± 2°C (ideal storing conditions or 'labcrete'). The compressive strength as well as the splitting tensile strength of the concrete was to be tested at 28 maturity days, together with the strength development after 1, 2, 3, 7, 14 and 28 maturity days. Strength measured in this way is meant to describe the potential strength of the concrete (understood as its strength without any 'disturbing' effects from transport, casting, compaction, and curing). Unacceptable strength measured on cast test specimens ('labcrete') can only be caused by failure in the constituent materials, in the composition or in the mixing (and in the testing).

The strength of concrete is probably the property most often subjected to testing. Compressive strength of concrete is described as a single property, but in fact, for one and the same concrete, it will depend on many parameters, e.g.:

- Maturity age of the concrete
- Geometry of the test specimen
- Casting technique used for production of the specimen
- Curing of the specimen (e.g. moisture and temperature)
- Speed of loading in compression test.

It is therefore obvious that the test method must be standardized down to the smallest detail and that the test specification must always be followed.

The requirements were divided into two categories: for strength and for production control (uniformity). The test frequency was to be one sample (of two cylinders) per 100 m^3 of concrete commenced.

a) Strength requirements

For each inspection section the required characteristic compressive strength at 28 maturity days, f_{ck}, had to be documented.

The decision rule for acceptance was:

Mean $\{f_c\} \geq 0.8\, k_n f_{ck}$ = accept

Here mean $\{f_c\}$ is the mean value of the compressive strengths measured, and k_n is specified in DS 411:

$$k_n = exp\left[\left(2.28 + \frac{1}{\sqrt{n}}\right)\delta - 0.1875\right]$$

where n is the number of samples.

Without any documentation, the value of the coefficient of variation is δ = 0.12 when 40 MPa ≤ f_{ck} ≤ 50 MPa. However, the Danish Code of Practice DS 411 allows for documentation in order to decrease the value of δ.

b) Production control

The value of the potential compressive strength during production should comply with the pre-determined upper and lower limits. The decision rule for acceptance was the method of control by alternatives, i.e. that the numbers observed outside the predetermined limits should be smaller or equal to those given in DS 423.1.

If the compressive strength values were outside the pre-determined range then the concrete mix design should be adjusted.

Achieved concrete strength

The strength of the concrete in the as-built structure is vital to its load-carrying capacity and safety according to code of practice DS 411. By determining the potential strength as well as the achieved strength it is also possible to decide where to look for a possible error, if an inspection section is rejected because of unacceptable strength.

The potential strength of the concrete can only be achieved under satisfactory conditions for transport, casting, compaction and curing.

The compressive strength of concrete in a structure can only be measured from that of concrete itself. This can be done by:

- Measuring the strength of samples drilled from the concrete.
- Measuring the strength directly of the concrete (in-situ test).

Therefore, FAB’s required pull-out testing with LOK-test and CAPO-test according to the in-situ test method DS 423.31.

By determining a large number of related values for pull-out force and cylinder compressive strength with a maturity ages from 1-35 days, the relationship between the two can be determined. The pull-out strength was to be determined for various conditions of curing. This was executed on special test blocks 900 mm x 900 mm x 500 mm. In this way, an internationally-accepted relationship was established for 'normal' concrete. For mortar the relationship is somewhat 'lower'. For the concrete types used at the Great Belt Link, studies showed that use of the internationally-accepted relationship was slightly conservative, perhaps because of the smaller content of coarse aggregate than in 'normal' concrete.

Requirements were set for the positions of a LOK-test insert and a CAPO-test insert in the concrete. Random checks of the geometry of the cutting and the drilling equipment as well as the failure mode were, therefore, part of the test procedure.

As part of the contract, the contractor's technicians had to attend a 2 days course where the theoretical background for LOK-test and CAPO-test was given as well as practical skills in how to perform the testing. The LOK/CAPO courses ended with an examination and the participants who passed received a diploma. Only the latter were allowed to perform this type of testing [7].

The requirements were divided into two categories: the strength requirement and the production control. The test frequency was 2 samples (each of 2 inserts) per 100 m^3 of cast concrete and at least 3 samples per inspection section. The testing should be performed when the concrete had attained an age of 28 maturity days.

a) Strength requirement

For each inspection section the characteristic achieved compressive strength at 28 M-days was required to be higher or equal to 80 % of the required potential compressive strength f_{ck}.

The decision rule for acceptance was:

Mean $\{f_c\} \geq 0.8\ k_n\, f_{ck}$ = accept

Here mean {f_c} is the mean value of the compressive strengths measured in-situ by pull-out test and k_n is specified in DS 411.

b) Production control

The value of the achieved compressive strength during production should comply with the pre-determined upper and lower limits. If the achieved compressive strength, determined by LOK-test were outside the pre-determined range then additional CAPO-test should be performed. If these pull-out strengths also were outside the pre-determined range, then adjustments of e.g. the curing procedures should be made.

The decision rule for acceptance was the method of control by alternatives, i.e. that the numbers of observation, which were outside the pre-determined limits should be smaller or equal to the numbers presented by DS 423.1.

Pretesting and trial casting

When the contractor had documented that the constituent materials satisfied the requirements, pretesting of the concrete was to be carried out to demonstrate that among other properties, the concrete strength was satisfactory. When the contractor had documented, through trial batchings, that it was possible with the proposed concrete mix design to meet the requirements for the properties and characteristics of the concrete, a full-scale trial casting had to be performed.

5. LOK and CAPO testing [8]

The fundamental principle behind pull-out testing with LOK-test and CAPO-test systems is that the test equipment, which has a specified geometry, will produce results (pull-out forces) that have a specified correlation with the compressive strength of the concrete. This correlation is determined by measuring the force required to pull-out a steel disc or ring embedded in the concrete against a circular steel backstop concentrically placed on the concrete surface.

The first method (see Figure 8) is called LOK-test ('LOK' is the Danish designation for 'punch') and is used where it is possible to place a steel disc in the fresh concrete. For hardened concrete, the second method (see Figure 9) is used instead. In this CAPO-test ('CAPO' stands for 'cut and pull-out'), a steel ring is inserted into the concrete and expanded to fit a specially drilled hole and routed recess in the concrete. The diameter of both disc and ring is 25 mm, the distance to the concrete surface is 25 mm and the inner diameter of the backstop 55mm.

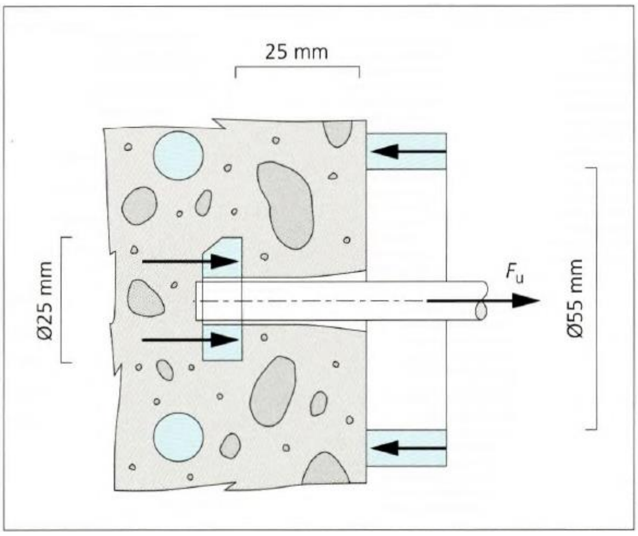

Fig. 8. The LOK-test principle. A steel disc 25 mm in diameter is embedded in the fresh concrete at a depth of 25 mm. After hardening of the concrete the disc is pulled against a steel backstop, 55 mm inner diameter, on the surface.

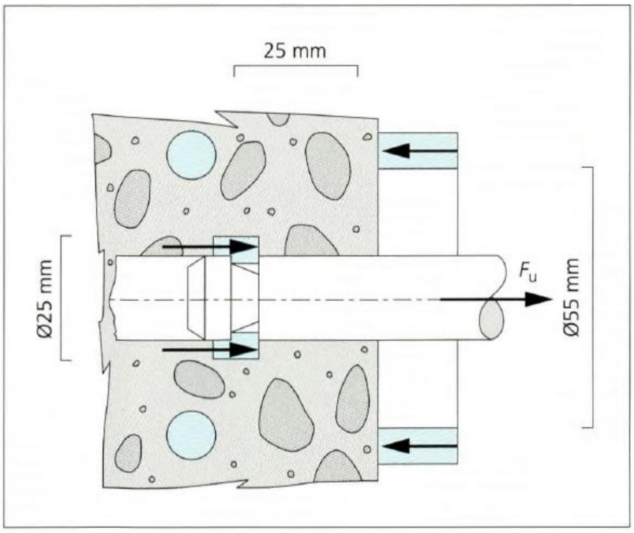

Fig. 9. CAPO-test principle. In a drilled and recessed hole, 25 mm below the surface, an expandable ring is inserted and expanded to fill the 25 mm diameter recess. In the test, the ring is pulled against a steel backstop, 55 mm inner diameter, placed on the surface.

Recommended correlation

To correlate the measured pull-out forces to an equivalent compressive cylinder strength, several tests were devised. The relationship between pull-out force and compressive strength shown in Figure 10 had been recommended and used for many previous works. A correlation test is in principle performed by determining the compressive strength on cylinders 150 mm diameter x 300 mm long and LOK/CAPO pull-out force on 200 mm cubes. The cylinders and cubes are cast in concrete from the same batch and vibrated identically. The compressive strength and pull-out forces are tested at the same maturity age and then at different maturity ages to cover the required strength range.

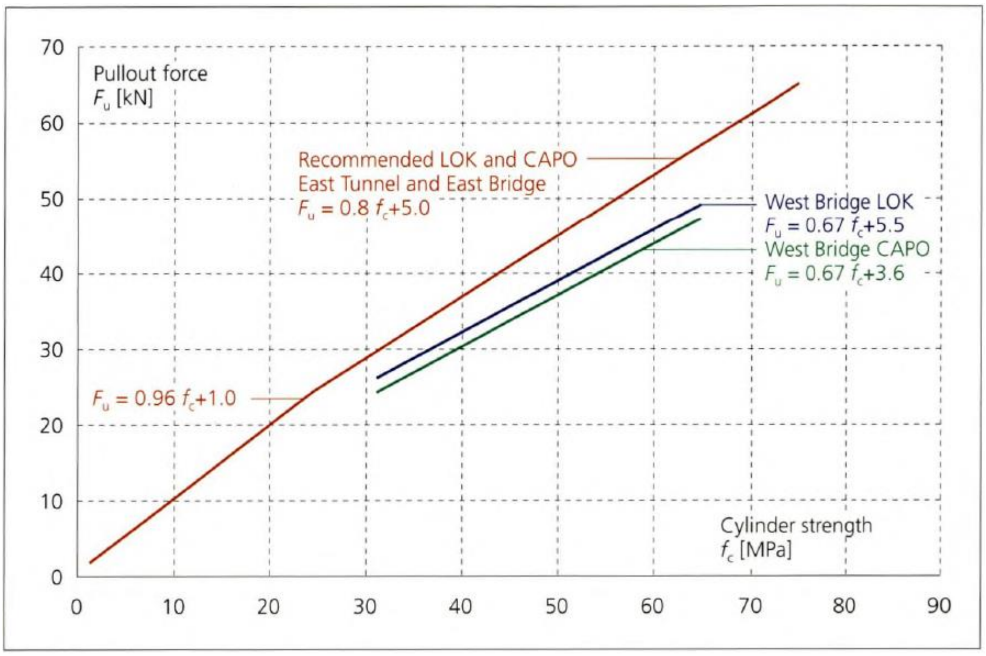

Fig. 10. Recommended correlation (red) between LOK-test and CAPO-test pull-out forces and 150 mm diameter x 300 mm long standard test cylinder compressive strength. This correlation was used for the East Tunnel and East Bridge whereas separate correlation relationships (blue and green) were established for the West Bridge.

Strength requirements for the Great Belt Structures

The specifications for the Great Belt structures required testing both of the potential strength by water-cured test cylinders (150 mm diameter x 300 mm long) and the achieved strength by in situ LOK/CAPO testing. The properties of the concrete cover in the built structure are important for its durability and it can only achieve its potential strength under satisfactory transport, casting, compaction, and curing conditions. By determining the potential strength as well as the achieved in situ strength, it was deemed possible to decide where to look for unsatisfactory conditions and to correct them.

In-situ strength testing had never before been used for production tests in Denmark, but on the Great Belt Link LOK-test bolts were used for all structures except the slipformed caisson walls (West Bridge) and the tunnel lining segments, where CAPO-test rings were inserted at the time of testing. The requirements for the 28 days' characteristic compressive strength are shown in Table 2.

	Mix type	Cylinder tests	LOK/CAPO tests
East Tunnel	A1	50MPa	40MPa
	B	45MPa	36MPa
East Bridge &	A	45MPa	36MPa
West Bridge	B	45MPa	36MPa

Table 2. Requirements to 28 days characteristic strength.

Correlation for the Great Belt concrete mixes

The recommended correlation (see Figure 10) was used for the East Tunnel and East Bridge. During pretesting and full-scale trial castings for the West Bridge it was realized that the CAPO strength level determined on the basis of the recommended correlation was significantly lower than the LOK strength level. The obtained values also indicated a potential risk for rejections, so it was decided to carry out a correlation test for the actual West Bridge concrete. For this purpose, several test blocks were prepared, each 400 mm x 200 mm x 200mm and fitted with four LOK-test bolts. After 4 maturity days, 6 blocks were LOK- and CAPO-tested and at the same time, 18 cylinders were strength-tested. The tests were repeated after 7, 28 and 56 maturity days and the average pull-out forces plotted against the cylinder strength. It was found that the West Bridge correlations (see Figure 10) for LOK- and CAPO-tests were not identical with the recommended correlation.

Production testing in general

The structures were subdivided into inspection sections, each of which was accepted or rejected after a specified statistical evaluation. The main quantities and number of required strength tests for the West Bridge inspection sections can be seen in Table 3.

Main quantities per inspection section	Concrete m^3	Number of LOK/CAPO test bolts	Number of test cylinders
Caissons (walls)	2 500-2 900	100-116	50-58
Pier shafts	700-1 200	28-48	14-36
Road girder	2 300	92	46
Rail girders	1 700	84	34

Table 3. Main quantities for the West Bridge inspection sections.

Production testing: West Bridge rail girders

As an example of production testing, the West Bridge rail girder inspection sections were tested by placing 84 LOK-test bolts at the same level inside the walls. It appears from Figure 11 that the cylinder and LOK-strength levels were almost identical from production start until November 1991. For the remaining production the LOK-strength level was some 10% lower than the cylinder strength level, either because of poorer concrete Work or the LOK-test performance itself. The concrete cover only complied with the requirements if the characteristic 28 days' LOK-strength was above 36 MPa.

The relation between the characteristic LOK-strength (f_{ck}) and the average 28 days' LOK or CAPO-test strength (f_c) was specified as:

$$f_{ck} = \frac{f_c}{exp\left[\left(2.28 + \frac{1}{\sqrt{n}}\right)\delta - 0.1875\right]}$$

where *n* is the number of tested sets of LOK-test bolts from the inspection section (one set = 2 LOK-test bolts) and δ is the coefficient of variation.

During production, the coefficient of variation for each element type was computed from the previous 100 test results. For example, for the rail girder production was found to vary from 0.08 - 0.14. For the rail girder inspection sections n was 84 (see Table 3).

The lowest characteristic value obtained in May 1992 (see Figure 11) was:

$$f_{ck} = \frac{42.5}{exp\left[\left(2.28 + \frac{1}{\sqrt{84}}\right)0.14 - 0.1875\right]} = 36.7 \text{ MPa}$$

which was just above the required limit of 36 MPa, and the quality was therefore acceptable.

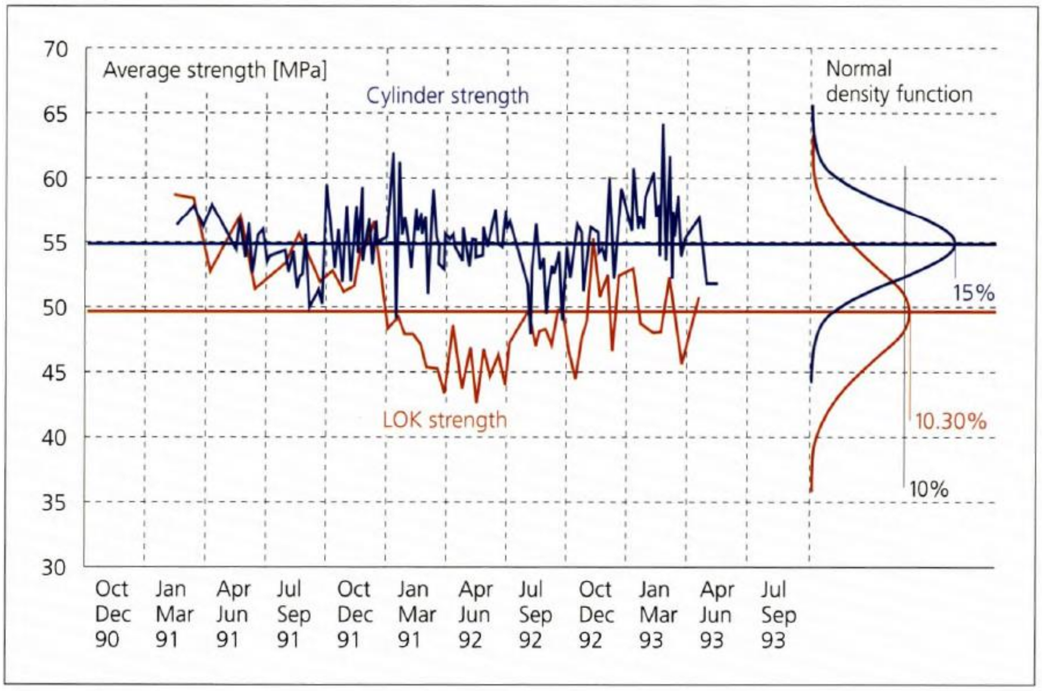

Fig. 11. West Bridge, rail girder inspection sections mix type B. Average strength results per inspection section of LOK-test and cylinder strength after 28 days. The average LOK-test strength for the entire production was 90% of the average cylinder strength. The coefficients of variation for the average LOK-test strength and average cylinder strength were 0.079 and 0.049 respectively.

Comparison of test results from the East Tunnel, East Bridge and West Bridge

Table 4 shows the results of a comprehensive statistical evaluation of the major part of the LOK/CAPO and cylinder strength tests for each of the Great Belt projects.

	Mix type	28 days LOK/CAPO strength		28 days cylinder strength		Relative
		Average $f_{LOK/CAPO}$ MPa	Coefficient of variation	Average f_c MPa	Coefficient of variation	Insitu strength level $f_{LOK/CAPO}/f_c$
East Tunnel	A1	58.2 CAPO	0.163 CAPO	76.4	0.060	0.78
East Bridge	A	55.4 LOK	0.116 LOK	55.8	0.076	0.99
	B	51.8 LOK	0.133 LOK	53.0	0.069	0.98
West Bridge	A	53.7 LOK	0.097 LOK	57.6	0.049	0.93
	B	50.1 LOK	0.077 LOK	55.4	0.051	0.90
	200	51.9 CAPO	0.195 CAPO	57.4	0.049	0.90

Table 4. Statistical evaluation of LOK/CAPO-tests and cylinder strength; the coefficients of variation are computed on the basis of the average results per inspection section. The LOK/CAPO strength results for the West Bridge are based on the established correlation relationship shown in Figure 10.

Based on the results shown, it can be concluded that:

- The relative in situ strength level was highest for the East Bridge
- The relative in situ strength level for LOK-testing was higher than for CAPO-testing
- The variation in 28 days' cylinder strength and LOK strength during the entire production period was rather small for the West Bridge and approximately 40% higher for the East Bridge

- The variation in 28 days' CAPO strength was significantly higher than the variation in LOK strength which in turn notably exceeded the variation in cylinder strength
- The extended curing period of 240 maturity hours for concrete type A generally resulted in a higher relative in situ strength level compared with the level for concrete type B, which was cured for 96 maturity hours.

Fig.12. Trial casting, tested for chloride diffusion, strength and LOK-Test / CAPO-Test of the cover layer in relation to maturity to establish acceptable intervals.

Fig.13. Training of the contractor´s technicians on performing LOK-TEST and CAPO-TEST. The training course was completed with an examination and issuing of a diploma.

Fig.14. Successfully completed CAPO/LOK-Test of the cover layer of an element.

Fig.15. LOK-Test inserts installed in wooden formwork before concrete casting.

Fig.16. LOK/CAPO-Test in progress.

6. Final remarks [9]

Preparation for the Great Belt Link concrete works started in the 1970's when the project was being planned, with construction due to start in 1978. Temperature curing was one of the major issues then and, to evaluate the effect of it and moisture curing development during hardening, two concrete walls were cast and investigated. When the project was postponed in 1978 for political reasons, the test walls were placed in the seawater at the present bridge alignment for later research.

When Storebælt recommenced the project in 1987, it was decided to base the requirements for the concrete work on all available practical and theoretical experience to obtain durability, strength and uniformity in the concrete structures. One of the measures was efficient quality assurance during design and construction.

As one of the major issues in the 1980's was chloride ingress into concrete, it was natural to examine the 1978 test walls to determine how that concrete mix had performed regarding chloride ingress. Investigations showed that if the Great Belt Link structures had been constructed with that 1970's concrete, the chlorides would already, after 11 years, have reached the reinforcement at a depth of 40 mm – 50 mm, enough for corrosion to start. Different technology to protect the reinforcement therefore had to be used by Storebælt to secure the service lifetime of 100 years for the Link.

Concrete durability became the major issue in setting up the specifications for the project, resulting in the use of low water/cement ratios, fly ash and silica fume, plasticisers, air-entrainers and improved aggregate type, together with requirements for protection against evaporation and big temperature differences during construction.

The importance of well-planned pretesting and trial castings for the actual work methods, and prior training of the workforce, was emphasized. Where this was neglected, the result was either complete demolition of the non-compliant structure or - if the time schedule did not allow for this – introduction of protective measures like cathodic protection to gain sufficient durability.

New test methods during production were put into practice on this project, including examination of the microstructure, and pull-out strength testing of the important protective concrete cover so as to evaluate the real quality of the hardened concrete in the structures and not just the potential quality based on laboratory evaluation. The test results varied widely, either due to variations in the concrete itself or in the test methods. Microstructure examination showed that some work methods (i.e. slipforming) created defects to such an extent that they had to be abandoned.

The use of microstructural analysis as an acceptance test method during production was questioned due to the limited test sample, but the information obtained was valuable in tracing uniformity from pretesting in production to verifying the mix control to locating possible grave defects in the concrete.

Regarding the use of pull-out testing (LOK and CAPO tests), it is a primary recommendation for production testing, provided that problems relating to training test operators, placing test bolts, and statistical evaluation of results are solved.

However, despite first class materials and mix proportions being optimized to secure durability, strength and uniformity, inadequate casting, vibration, compaction, and curing can completely destroy the quality of the final structure. Experience from the Great Belt Link shows that high performance concrete requires thorough pretesting of the fresh concrete properties to determine adequate work procedures and to train site staff in these before start of work.

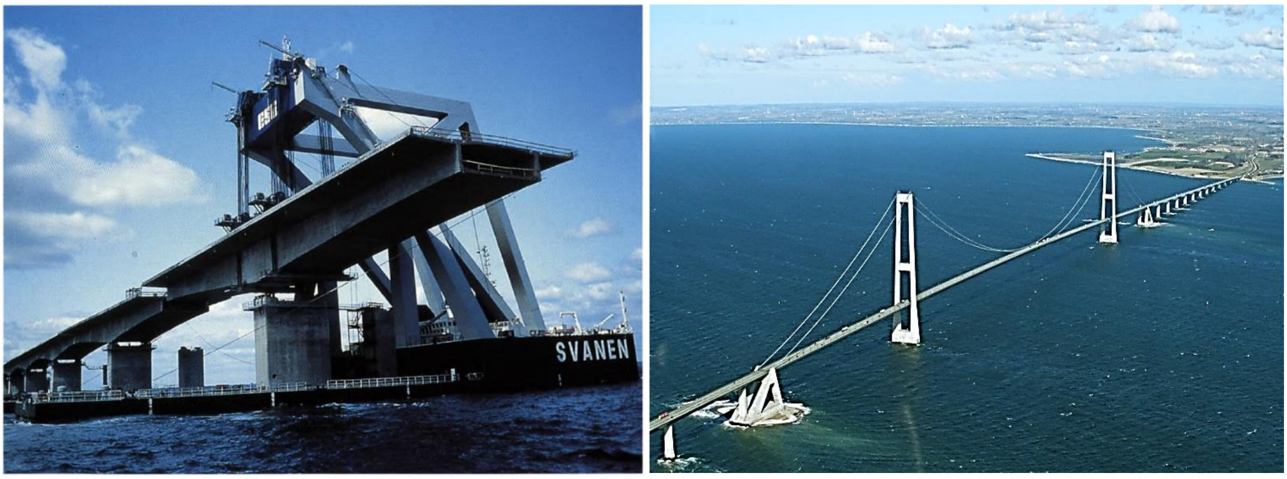

Fig.17. The West (left) and East (right) bridges of The Great Belt Link Project.

7. References

(1) www.sundogbaelt.dk (retrieved January 2015), “facts about Storebalt”.
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(3) Concrete Technology, A/S Storebæeltsforbindelsen, Copenhagen, Denmark, 1999, Pages 12-14.
(4) Concrete Technology, A/S Storebæeltsforbindelsen, Copenhagen, Denmark, 1999, Pages 15-22.
(5) Concrete Technology, A/S Storebæeltsforbindelsen, Copenhagen, Denmark, 1999, Pages 45-47.
(6) Concrete Technology, A/S Storebæeltsforbindelsen, Copenhagen, Denmark, 1999, Pages 67-71.
(7) Concrete Technology, A/S Storebæeltsforbindelsen, Copenhagen, Denmark, 1999, Page 252.
(8) Concrete Technology, A/S Storebæeltsforbindelsen, Copenhagen, Denmark, 1999, Pages 169-173.
(9) Concrete Technology, A/S Storebæeltsforbindelsen, Copenhagen, Denmark, 1999, Pages 269-270.