TR24

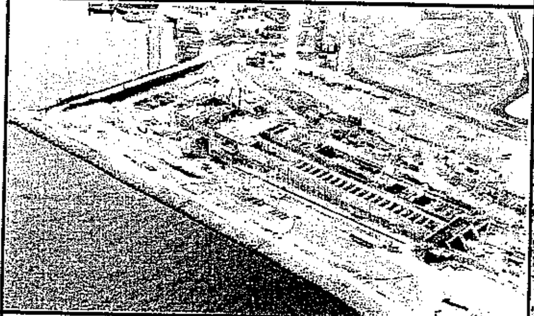
THE Concrete Conference

TECHNICAL PAPERS

THE
DYNASTY
HERITAGE
ROTORUA

5-7
OCTOBER
2001

October 2001



THE Concrete Conference
'Teamwork A Formula for Success'

Technical Conference and AGM's
The Dynasty Heritage Rotorua
5 – 7 October 2001

Conference Programme and Table of Contents

For further copies of this volume, designated Technical Report (TR) 24 - Price: $60.00 (inclusive GST) and are available from: THE Concrete Conference, P O Box 12, Beachlands, Auckland, New Zealand Phone: (09) 536 5410, Fax: (09) 536 5442, Email: concrete@bluepacificevents.com

Joining two nations: Concrete for the Øresund Link

Ulla Kjaer[1] & Mikael W. Braestrup[2]

SUMMARY

The Øresund Fixed Link between Denmark and Sweden is formally owned by the governments of Denmark and Sweden, and opened July 1st 2000. The Link comprises a 16-km motorway and railway connection across the strait Øresund between Copenhagen in Denmark and Malmö in Sweden. Its main elements are:

- An artificial Peninsula off the Danish coast near Kastrup Airport
- A 4050 m immersed tube tunnel
- A 4055 m artificial island
- A 3014 m western approach bridge
- A 1092 m cable-stayed high bridge
- A 3739 m eastern approach bridge.

The funding of the Link is by loans from the international money markets. Since the Danish and Swedish states have guaranteed the loans financing conditions have been particularly favourable. The loans will be repaid from the motorway tolls and other revenue from the future users of the Link. The earnings will also cover the cost of the onshore works, which amounts to one third of the total approximately USD 3,000 million construction costs.

A total of 1 million m^3 of concrete was used to construct the Link, some of it produced as far away as Cadiz in southern Spain, where the approach bridge girders were manufactured.

The immersed tunnel was constructed from 20 precast elements, lowered onto the seabed. 8 match-cast segments constituted each element each comprising 2700 m^3 of concrete cast in one continuous pour. This was the first time this method of precast segmental construction was used for a structure on this scale.

No exterior lining was used for the tunnel; the concrete structure had to provide the barrier against the sea; this involved extensive pre-testing and trial casting, as well as planning calculations of the crack risk.

Element # 13 sank unexpectedly during lowering, but was salvaged. The Multi Purpose Pontoon used for placing the elements on the sea bottom was involved in a collision, and a total of 15 unexploded bombs dating back to the Second World War were found on the sea bottom. In spite of these - and other - incidents, the Link opened before time and within budget.

OVERVIEW OF THE WHOLE PROJECT

- **GENERAL**

Treaty and funding [1]

The Swedish and the Danish governments signed the treaty for the Øresund Link in March 1991. The users pay the Link: the road traffic pays toll (in 2001 the one-way price for a car is DKK 230, approximately US$ 30) and the railway operators pay a fixed yearly fee (in 2001 the price for a one-way train ticket is DKK 60, approximately US$ 7.50).

The joint Owner company, Øresundskonsortiet (as an Operator renamed Øresundsbro Konsortiet, or simply Øresundsbron) was formed in 1992 with a fairly small share capital. The Swedish partner is the company SVEDAB AB which is owned by the Swedish government through the national road and rail administrations.

---

[1] *Chief Consultant, RAMBOLL, Denmark*

[2] *Chief Consultant, RAMBOLL, Denmark*

The Danish partner A/S Øresundsforbindelsen is owned by the Danish government through the holding company Sund & Bælt, which also owns the toll-funded Storebælt Link, fully operational for road and rail since June 1998.

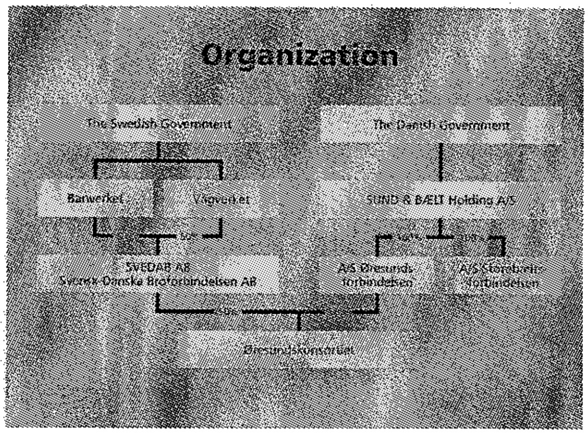


Figure 1 *Organization [3]*

The joint venture partners are in charge of respectively the Swedish and the Danish landworks.

The funding is obtained by international loans guaranteed jointly and severally by the two governments. Because of this the real (i.e. inflation-adjusted) interest rate obtained is less than 4%, which is much lower than the 10% normally required by private investors. Consequently, a short payback period of 25 – 30 years is predicted at an initial average annual daily traffic of 11,000 vehicles.

During the first year of operation, however, the actual road traffic has not been as high as expected, resulting in a somewhat increased payback period being envisaged. The total construction cost of the coast-to-coast structure is US$ 2,000 million (1990 prices). In addition, the cost of the complete onshore works is about 50% of that figure.
Subsidies from the EU Commission to the Øresund Link total DKK 950 million or about 6% of the total construction cost for the coast-to-coast section.

Contract philosophy [2]

The contract type is design-and-construct. The design-and-construct concept implies that the contractors carry out the detailed design. The Owner together with his Consultants prepared a conceptual tender design based on functional criteria, fixing alignment and principal dimensions, as well as aesthetic, environmental and safety criteria, but leaving the detailed design to the Contractor. You might say that the Owner defined what he wanted and the Contractor chose how to achieve it.

In order to provide some kind of safety net against the Client-Contractor relationship breaking down during the contract period and claims arising, Øresundskonsortiet included the formation of a Dispute Review Board (DRB) as part of each contract. Each board was made up of "three wise men" nominated jointly by the contractor and client and it acted as an independent body with specialist technical knowledge. The DRB visited the site every six or eight weeks to collect information from contractors and client and listen to any grievances.

If a dispute occurred, the DRB would consider the case and recommend a course of action which both parties must follow. If either party was unhappy with the decision, they would be free to go to litigation but not until the job was complete.

In practice it worked very differently; neither Øresundskonsortiet nor any of the contractors ever had to ask the DRB to rule on a dispute [6].

Eurocode application [2]

With two sets of national Codes of Practice and standards and with the European Community long established and both countries being members, it was decided to apply the structural Eurocodes. However, at the time of tender most of these only existed as drafts or ENVs, so a Project Application Document (PAD) was prepared. The scope of the PAD is similar to the National Application Documents (NADs), prepared by the CEN member countries implementing the Eurocodes.

The partial safety and load combination factors are determined by reliability calibration to a target reliability index of β = 4.7, specified by Øresundskonsortiet. Influence models are used to calculate statistical representations of the stress resultants on the basis of statistical information on the loads. It follows that the safety factors are dependent on the influence models, and thus on the considered structure. Consequently, different sets of partial safety factors and load combination factors shall be used on different structures, although the structural reliability is the same. Using the same partial safety factors on material properties and having different load and load combination factors, specified in the relevant Design Basis document, achieve this.

The reliability calibration leads to a significant reduction in the traffic load factors, particularly the load combination factors. This is most important for the bridge, which has to carry road traffic in combination with high-speed passenger trains and heavy freight trains.

Safety concept [2]
The safety concept stipulated that the risk of using the Link should be comparable to that of using the ordinary transportation infrastructure in the two countries.

To evaluate whether the risk policy goal has been achieved, a comparable risk measure is defined as the average fatality risk on Danish and Swedish motorways and railways, per one billion passages on a stretch corresponding to the total length of the Øresund Link. The analyses show that the risk for the road users on the Øresund Link is less than the corresponding risk for transport on ordinary motorways. For railway users the risk is at the same level as for transports on railways in Sweden and Denmark.

For the Øresund Link the risk analysis has interacted with the Design Basis in the rational treatment of rare accidental load cases, notably ship collision with bridge piers and girders, as well as fire scenarios.

The design load is determined as the worst case with a recurrence interval corresponding to the specified reliability index. More severe – and less frequent – events are considered in the operational risk analyses, and risk mitigation measures are introduced if the specified Risk Acceptance Criteria are not satisfied.

Additional costs of approximately DKK 241 million were incurred for safety, mainly as a consequence of the Danish authorities' demands for the sea traffic in Drogden channel, the Swedish authorities' demand for realignment and excavation of the Flinträнnen channel, searches for bombs on the construction site and improved fire safety in the tunnel.

Contract documents
The contract documents included design requirements (including the PAD and definition drawings) and construction requirements (both to materials and execution).

Public hearings
Like for the previous large infrastructure project in Denmark, the Storebælt Link, public opinion was in the beginning negative towards the project, but public hearings gradually turned the opinion around.

Tendering
The pre-qualification of tenderers was completed in 1993; at that time the contract and tender principles had been established. Six contractors were pre-qualified for each major contract. The tenderers were not compensated for their participation. Enquiry documents were issued in 1994. These instructions to the tenderers specified the selection criteria. Mainly this was "the economically most advantageous tender".

Risk-sharing
Risks outside the Contractor's power (e.g. concerning geotechnical conditions) were shared. A reference condition and a corresponding lump sum was defined. Anything outside of the reference conditions resulted in time extension and price increase.

Contracts
The three major construction contracts: Dredging & Reclamation, Tunnel, and Bridges were signed in 1995, later followed by Installation contracts. The scheduled completion of works and handing over was in March 2000,

less than 5 years later, with start of commercial operation envisaged in September 2000.

Payment milestones

At the start of each contract the Contractor was given an advance payment to cover mobilisation costs, the philosophy being that the Owner was able to borrow money internationally at much lower interest rates than contractors were. Within the contracts the Contractors defined payment milestones.

Quality Assurance

Under a design-and-construct contract the Contractor carries out self-control. This was verified by joint audits by the Owner, his Consultants and the Contractor's QA organisation.

Environment

The Link is located just south of the island Saltholm, which is a protected bird and seal sanctuary, and off limits to any construction activities. Øresund is one of the main in- and outlets for the Baltic Sea. Because of this, and in view of the very extensive dredging and reclamation works, the Danish and Swedish environmental authorities specified a so-called "zero blocking solution". In practise this meant that the net blocking effect of the structures on the flow of water through Øresund should not exceed 0.5 %, and that figure should be reduced to zero by compensation dredging. In addition, a maximum sediment spill of 5% only was permitted, and 24-hour survey and spill monitoring was required and audited.

Additional costs of approximately DKK 193 million were incurred for the environment to meet demands from the authorities for permissions to dig, reporting in connection with the authority control and inspection programme, the construction of baffle walls and noise reduction for the railway, as well as contribution towards environmental work on Lernacken [1].

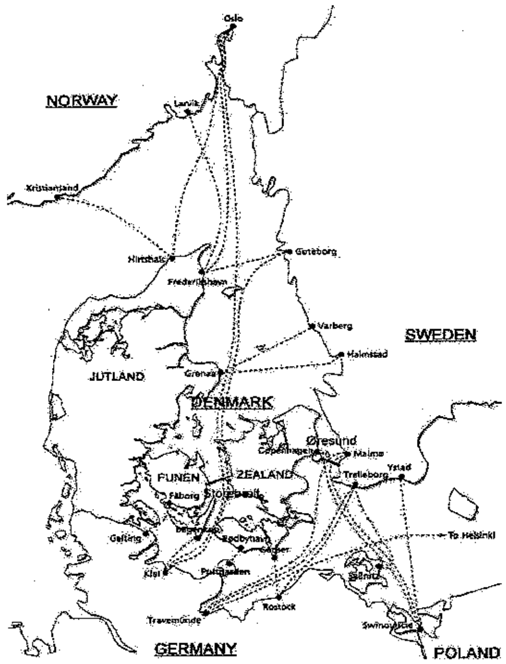


Figure 2 *Traffic links between Scandinavia and the European Continent*

▪ DREDGING & RECLAMATION

The D&R contract included construction of an artificial 0.9 km^2 peninsula next to Copenhagen Airport and an artificial 1.3 km^2 island (named Peberholm) south of Saltholm, relocation and deepening of the secondary navigation channel Flintrännen, dredging of the tunnel trench, compensation dredging (to compensate for the reduced sea water flow due to the artificial island and peninsula), and temporary work harbours and access channels. Approximately 7 million m^3 of gravel, stone, clay till and limestone with flint deposits were moved.

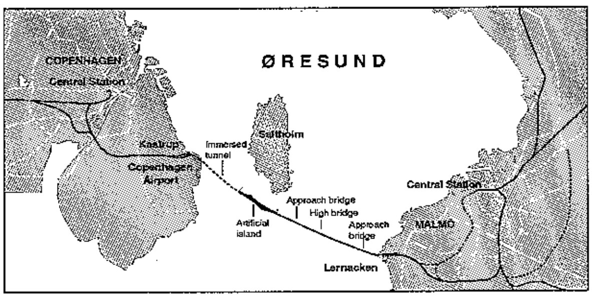


Figure 3 *Coast-Coast Section of the Øresund Link [3]*

Peberholm will not be landscaped and planted, but seeds brought by birds from the neighbouring island of Saltholm (which is a protected wildlife reserve) will take root.

The house consultants for the D&R contract as well as for the Tunnel contract were the Øresund Link Consultants (ØLC). ØLC is a joint venture between RAMBOLL (DK), Scandiaconsult (S), Sir William Halcrow & Partners (UK) and Tunnel Engineering Consultants (NL) in association with architects Dissing + Weitling (DK).

The contractors were the Öresund Marine Joint Venture, consisting of Per Aarsleff (DK), Ballast Nedam Dredging (NL) and Great Lakes Dredge & Dock Company (USA).

- **BRIDGES**

The bridge construction was originally tendered as two contracts, one for the High Bridge and one for the Approach Bridges. Two variations were tendered: a single-level and a two-level solution. The two-level bridge attracted the lowest bids from essentially the same group, and the two contracts were combined. The high bridge has a 490 m navigation span with a minimum 57 m clearance. The road traffic is carried on the upper deck and the rail traffic on the lower level, with emergency walkways and staircases to the upper level at maximum 600 m spacing.

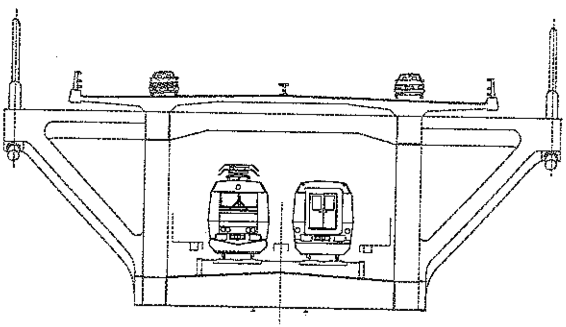


Figure 4 *Cross-section [3]*

The contract intentions were met fully by the contractor: a high degree of factory-like pre-fabrication, repetition of design and construction details, and use of existing facilities and equipment. Caissons, pier shafts and railway troughs were pre-fabricated in a construction yard at Malmö North harbour. The two pylon caissons were pre-fabricated in Malmö Central harbour in a discontinued dry dock. Approach span steel trusses, including concrete road deck, were pre-fabricated in Cadiz in Southern Spain. Steel sections for the cable-stayed high bridge were pre-fabricated all over Scandinavia, and assembled at the Malmö construction yard, where the road deck was also concreted. Pylon towers were cast in-situ using climbing formwork. The heavy lift vessel 'Svanen' ('The Swan') used for installation of the pre-fabricated parts had a lifting capacity of 8,700 ton.

The house consultants for the Bridges contract were the ASO Group (ASO). ASO is a joint venture between Ove Arup & Partners (UK), SETEC (F), Gimsing & Madsen (DK) and ISC (DK) with architects Georg Rotne (DK).

The contractors were Sundlink Contractors (SLC). SLC is a joint venture between Skanska (S), Hochtief (D), Monberg & Thorsen (DK) and Højgaard & Schultz (DK).

- **TUNNEL**

The Tunnel contract included fabrication, transportation and installation of immersed tunnel elements. It also included construction of ramps and portal buildings and outfitting of the tunnel with road works and installations.

The house consultants were ØLC (cf. 'Dredging & Reclamation above) and the contractors were the Øresund Tunnel Contractors (ØTC). ØTC is a joint venture between NCC International (S), GTM International (F), John Laing (UK), E. Pihl & Søn (DK) and Boskalis Westminster (NL).

- **ONSHORE WORKS**

The onshore works on both sides of the Link comprise road and railway connections. On the Danish side they include a 9 km traffic corridor (680 m of which are covered) across the island Amager, for both motorway traffic, freight trains and electrified passenger trains, and an underground station at Kastrup Airport. On the Swedish side they include connections to the existing railway and motorway networks. A future, independent project will construct the socalled Malmö City Tunnel, taking the trains under the city to the central station.

CONSTRUCTION OF THE IMMERSED TUNNEL

The proximity of the main shipping lane to Copenhagen Airport necessitated a tunnel rather than a (high) bridge across the Drogden navigation channel.

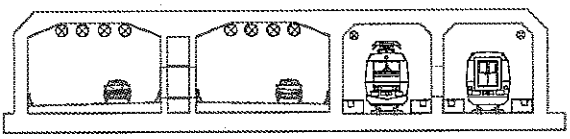


Figure 5 *Cross-section of Tunnel [3]*

Design philosophy

The tunnel is constructed without water-tight membrane, meaning that the concrete walls must be watertight and crack free. A major crack risk occurs during casting due to restraints and differential temperature movement.

The winning Contractors reduced that risk by producing tunnel segments in a purpose-built casting yard and casting each segment in full profile in one continuous pour of 2700 m^3 of concrete, lasting approximately 30 hrs. This way production was also sped up. In addition they applied production techniques developed and tested in the construction of bridges over the last 20 years to tunnel construction: match casting and incrementally launching of segments weighing up to 7,000 t.

Factory conditions were achieved by the erection of sheds where the reinforcement was assembled and prefabricated. A central shed covered two production lines where two segments were cast simultaneously per week in order to meet the time schedule.

Tunnel segments and elements [3]

The immersed part of the tunnel consists of 20 elements, each approximately 175 m long, resulting in a total immersed tunnel length of 3,510 m. Each element is made from 8 segments, joined together by temporary prestressing. The outer cross-sectional dimensions are 8.6 m by 38.8 m, and the element weight is approximately 56,000 t.

When the last segment is ready and joined with the previous 7 segments the entire element is jacked out of the shed. Two tunnel elements are produced in parallel and when finished they are jacked to the end of the skidding beams. The sliding gate to the production facility and the floating gate to the sea are then closed, and water is pumped into the basin to a level of 9.9 m above sea level. The two elements, resting on the skidding beams, are ballasted in such a way that they will float in level position.

Once afloat the elements are pulled towards the deeper end of the basin and each one is moored at two dolphins. The water in the basin is then lowered back to sea level, the floating gate is opened, and one by one the elements are towed out by tugs directly to the tunnel trench or to a temporary mooring location near the casting yard, depending on weather conditions or work progress at the trench.

The transportation distance to the tunnel site was 18 km. A keel clearance of 1 m was specified. The towing configuration was with two leading tugs and two assisting tugs i.e. one at each corner of the element. As the transportation was immediately followed by the immersion process a catamaran type pontoon and hoisting points were already attached to the element at the start of tow-out. As soon as the element was towed into position in the trench mooring lines were connected to anchors laid out in the vicinity of the trench.

Before start of any trench operation cleaning had been performed to ensure that no soft material was left. The elements were placed in a pre-dredged trench and founded on a gravel bed. The element was lowered onto the gravel bed and guided into relative position by the use of tapered guides mounted on the previously placed element. If the element was found to be out of tolerance, hydraulic jacks mounted in the exterior walls at the immersion joint were used to realign the element. Finally the element was ballasted to a safe minimum dead weight.

The first 15 elements were installed from the Kastrup end, the last 5 being installed from Peberholm. Thus the closure joint was located between elements no. 15 and 16.

Backfilling along the sides and on the roof is designed to offer a permanent cover and protection of the tunnel in all situations. The final tunnel profile is in general below the seabed level. At the Drogden navigation channel the top of the cover is 10 m below water level. The rock cover is designed to withstand a falling or dragging anchor or a sunken ship. Furthermore, the protective layer is stable against scour and erosion caused by currents or ship propellers.

Segment joints and immersion joints
The joints between segments were fitted with continuous waterstops with groutable tubes. Temporary prestressing cables, which were cut after placing, held the 8 segments together during tow-out and lowering. The immersion joints were fitted with steel frames and GINA rubber profiles, and after final placing OMEGA joint seals were installed and concreted.

CONCRETE AND EXECUTION

- **PRE-TESTING UNDER TIGHT TIME RESTRAINTS [4]**

The tunnel contract was signed July 1995 and ØTC began pre-testing immediately.

For concrete type A for Tunnel Elements it was imperative to determine all relevant properties as soon as possible, in order to carry out preliminary analyses of the early-age crack risk.

For concrete type B for Approach Works structures ØTC planned to cast these in situ using internal cooling by cast-in cooling pipes as necessary, so early-age crack risk analyses were not nearly as pressing. However, most of the Approach Works structures are exposed to frost and thus this concrete had to be frost resistant. The Contract requirements to pre-testing in relation to frost resistance were extensive.

Constituent materials
Preliminarily, all constituent materials had to be pre-tested. A total of 1 cement type, 3 fine aggregate types, 3 coarse aggregate types, 3 brands of admixtures – and 3 types of each brand, 2 types of flyash, 1 type of microsilica and 3 types of water was pre-tested.

The test that had the longest duration was alkali reactivity of coarse aggregate (according to CAN A23.2-14A) that lasts 52 weeks. The corresponding test of fine aggregate (according to TI-B 51) lasts 20 weeks.

Trial mixing
Initial trial mixing of concrete had to be performed on a batch plant of same type and fabricate as the production plant. For concrete type B the initial trial mixes and pre-testing was done in Halsskov on the former Storebælt site.

A number of properties were specified to be included. The experience from Storebælt had shown that it was difficult to achieve sufficient air content and frost resistance for hardened concrete in the structures. Because of this, one requirement was that at least 3 concrete mixes with different combinations of air-entraining and plasticizing admixtures should be pre-tested. For each mix, at least two levels of air content should be tested and testing included frost resistance.

ØTC pre-tested a total of 7 different concrete mixes each at both high and low air content.
Pre-testing of frost resistance was specified to include both salt scaling according to SS 137244 procedure I (laboratory cast specimens) and procedure III (drilled out specimens) continued until 112 cycles, and critical dilation according to ASTM C 671 with specimens stored in water up to 24 weeks.

Of the total of 2 x 7 = 14 mixes pre-tested all complied with frost resistance requirements to laboratory cast specimens. Almost all mixes with high air content showed good frost resistance of cores, whereas only 3 mixes with low air content complied.

Final pre-testing
Final pre-testing of concrete had to be done on the actual production batch plants, but this did not include frost resistance and therefore the duration was shorter.

Full-Scale Trial Casting

Full-scale trial casting was not allowed to start until the pre-testing of the concrete mix was completed and should be done using the proposed construction methods and equipment and performed by operators and staff who would be involved in the execution of the concreting works.

Among many other properties frost resistance testing according to SS 137244 procedure I and III was required, however only up to 56 cycles.

ØTC cast a slab and wall as their full-scale trial. However, the air content and frost resistance of the wall did not comply so an additional wall had to be cast after adjustments of the mix design and the execution.

The final documentation and approval of ØTC concrete type B was achieved Dec 1996, 18 months after Contract award, more than 12 months after pre-testing was begun, and 1 month after start of production.

- **COMPARISON OF DIFFERENT CONSTITUENT MATERIALS IN RELATION TO CRACK RISK, PRODUCTION CYCLE AND DURABILITY [4]**

A very important topic during the development of the concrete for casting of tunnel elements was of course the choice of constituent materials for the mixes. The decisions regarding which materials to use were taken in certain sequences and as a result of different tests and evaluations.

At tender stage it was decided to use blast furnace slagcement for the pre-fabrication of the tunnel elements. The slow heat development during the curing was considered a big advantage and the high durability of concrete with slagcement in a marine environment is well known. The corresponding slow strength development was however a concern as it could be difficult to achieve the necessary production cycle for tunnel segments i.e. one segment per week per production line.

At a relatively early stage of the project ØTC became aware of certain investigations carried out at the Technical University in Luleå, Sweden. A comparison of otherwise equal mixes, some with slagcement and some with ordinary portland cement, had been performed. The comparison only focused on the risk of early age cracking but it was based on the method for casting of tunnel elements chosen by ØTC and all the requirements for the concrete as specified by Øresundskonsortiet.

The conclusion of this comparison was that the risk of early age cracking was lower for a concrete mix based on portland cement. This result surprised ØTC and it was decided to investigate the matter thoroughly. At that time only laboratory testing was possible and testing of six different laboratory mixes was therefore decided.

The scope of the testing comprised a comparison of one blast furnace slagcement with two types of Ordinary Portland cement (with some addition of flyash) and also a comparison of two different types of aggregates. It was assumed that the two types of aggregates could influence the development of the E modulus and the strain-capacity of the concrete in different ways. Microsilica was included in one of the slagcement mixes as an experiment even though microsilica was not allowed together with this type of cement by the specification prepared by Øresundskonsortiet.

The six, otherwise equal, testmixes can be described as follows:

1a: Slagcement + aggregate type 1
1b: Slagcement + microsilica + aggregate type 1
1c: Slagcement + aggregate type 2
2a: Portland cement type 1 + flyash + aggregate type 1
2b: Portland cement type 2 + flyash + aggregate type 1
2c: Portland cement type 1 + flyash + aggregate type 2

The laboratory testing of the six mixes comprised all the properties necessary to perform proper temperature and stress calculations for a tunnel segment during hardening. As expected the heat development as well as the strength development was relatively slow when the concrete contained slagcement.

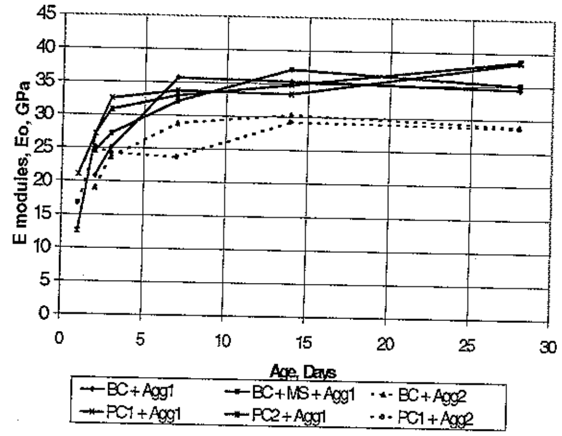


Figure 6 *E modulus development of the 6 mixes [4]*

Figure 6 shows the six E modulus developments. In this figure the four mixes with aggregate type 1 are shown with solid lines. Aggregate type 2 clearly produces the lowest E modulus regardless of type of powder.

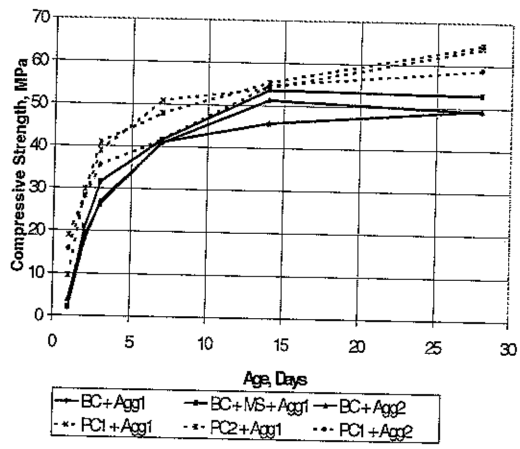


Figure 7 *Compressive Strength development of the 6 mixes [4]*

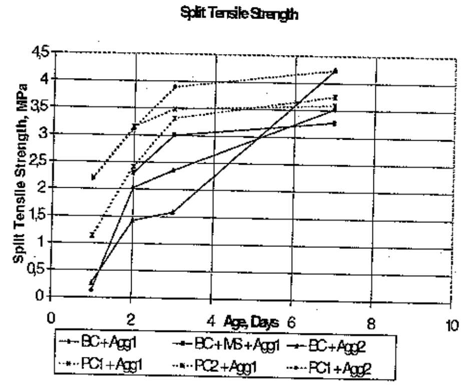


Figure 8 *Split Tensile Strength development of the 6 mixes [4]*

Figure 7 shows the six compressive strength developments and Figure 8 the tensile strength developments during the early phase. The solid lines represent the three mixes with slagcement.

ØTC used the Dutch company Intron for the verification of the necessary safety against formation of cracks. Intron was asked to execute new comprehensive temperature and stress calculations for the tunnel segment casting with input data from each of the six concrete mixes tested.

The result of these new calculations can be summarized as follows:

- The risk of cracking was only a little higher when using portland cement / flyash compared to slagcement (everything else equal).
- The risk of cracking was substantially lower when using aggregate type 2 compared to aggregate type 1 (everything else equal).
- The compressive strength development when using slagcement was so slow that the production cycle assumed by ØTC could not be met.

Based on the above it was decided to use portland cement, flyash and aggregates type 2. (The two types of portland cement tested showed more or less the same results).

When testing of concrete mixes produced on the batching plant on site became possible also mixes with three powders - portland cement, flyash and microsilica - were examined.

High workability of the fresh concrete was necessary due to the difficult conditions for placing and compaction in some parts of the segments. Even small amounts of microsilica improved the stability of the fluid concrete. The addition of microsilica also improved the durability of the hardened concrete, as the resistance against chloride ingression became markedly better. The use of a reasonable amount of Microsilica - a little more than 3 % of powder - was decided. (The maximum allowed according to the specification prepared by Øresundskonsortiet was 5 %, but high amounts were also avoided due to possible excessive early age chemical shrinkage contributing to increased risk of cracking).

When the powders and the aggregates had been decided only the choice of admixtures remained. A large number of different brands and types of admixtures were thoroughly tested and compared. Air entraining was an option but no requirements for air content or frost resistances were specified for tunnel segments. Mixes with and without entrained air were tested.

The control of the properties of the fresh concrete and - more important - the essential precise control of the density of the hardened concrete in the immersed tunnel elements was of course much easier without air entrainment and the possible big variations in the air content of the concrete. It was consequently decided not to use air entrainer.

When the different mixes with various admixtures were tested and their properties compared, workability / stability of the fresh concrete and durability of the hardened concrete were of course again important topics. Fortunately the same mix showed the best results both with regard to the properties of the fresh concrete and with regard to the resistance against chloride ingression in the hardened concrete (best results both when testing according to ASTM C 1202 and when testing according to APM 302). As frost action is not a topic in relation to the tunnel elements chloride ingression must be considered the most important mechanism of deterioration. The admixtures used in this mix were of course chosen.

For plasticizing the product used was composed of two parts pure melamine and one part stabilizer. The stabilizer was an ethylene-derivate, which adds thixotropic qualities to the concrete. For adjusting the setting time a retarder, a sodium gluconate, was used.

	kg/m^3
Cement PC (A/HS/EA/G)	324 kg
Flyash	52 kg
Microsilica slurry (50% water)	24 kg
Water	123 kg (Total water 143 kg)
Retarder	0.40
Plasticiser	10.50
Fine aggregate 0/2 mm	633
Coarse aggregate 2/8 mm	404 kg
Coarse aggregate 8/16 mm	476 kg
Coarse aggregate 16/25 mm	374 kg

Figure 9 *Concrete type A: Mix proportions [4]*

The final mix design (the final basic mix design - other variants exist) as used in the production is included as Fig. 9.

- **SELFCOMPACTING CONCRETE FOR THE CLOSURE JOINT [4]**

The closure joint was a short, approx. 1.35 m long, piece of in situ cast tunnel closing the last gap between tunnel elements no. 15 and 16.

Construction of the closure joint took place inside a watertight steel structure (cofferdam) installed along the entire circumference of the tunnel tube. Casting of the bottom slab and wall sections was possible with standard casting techniques and normal concrete. The closure joint roof slab was much more difficult. The entire concrete volume had to be pumped into a cavity closed on all sides. The casting included many obstacles for the concrete (reinforcement, water stops, cooling pipes etc.) and compaction by e.g. vibration was not possible. It was necessary to develop a fully selfcompacting concrete for this single casting with a volume of approx. 80 m^3.

One of the partners of ØTC - Dumez-GTM - was participating in a European research and development project regarding selfcompacting concretes and the - on site - development of the ØTC closure joint concrete was based on valuable information from this source. A very relevant piece of test equipment for testing workability, the L-box, was introduced for the testing of this concrete. The L-box test measures the flow of the concrete by gravity through a narrow grid of reinforcement and any tendency to segregation is immediately detected. Only completely stable and extremely workable concretes can pass this test.

The starting point for the development was the existing mix used for casting of tunnel segments. This mix already showed a remarkable high workability. A further development of this mix without new admixtures however turned out to be not possible. Increased workability could not be achieved without segregation. The stabiliser used in the existing mix, an ethylene-derivative, could not perform as necessary for this purpose.

The new admixture that was introduced in the mix was a stabilising viscosity agent. It is a powder, a kind of natural polysaccharide, added to the mix in very small amounts. It has been used in Japan for selfcompacting concretes for some time already. A somewhat longer mixing time is necessary in order to disperse the powder in the concrete. (A dilution of the powder in water is a possibility but even a small amount of powder requires a relatively big amount of water).

The most important "secrets" behind the new selfcompacting concrete developed by ØTC can be summarised in the following way:

- A high content of powder. ØTC used a total of 473 kg of powder per m^3.
- A high content of plasticizer. ØTC used 14 kg of melamine formaldehyde resin per m^3.
- A very carefully developed combined grading curve for the aggregates (the maximum grain size was 16 mm).
- A special admixture, a stabiliser, as explained above.

The importance of the fine-tuning of the combined grading curve must be emphasised. Even small differences in the combination of the available aggregates in the mix could result in radical changes in workability and tendency to segregation. The L-box test was eminent to show important differences in the quality of the mixes.

The ØTC mix design is summarised in Fig. 10 below. (The equivalent water/cement ratio was 0.39).

	kg/m^3
Cement PC (A/HS/EA/G)	380 kg
Flyash	70 kg
Microsilica slurry (50% water)	45 kg
Water (added water)	143 kg (total water 174 kg)
Stabiliser	0,150 kg (150 grams)
Plasticiser, melamine formaldehyde resin	14 kg
Fine aggregate 0/2 mm	750 kg
Coarse aggregate 2/8 mm	290 kg
Coarse aggregate 8/16 mm	710 kg

Figure 10 *Mix design for selfcompacting concrete [4]*

A comprehensive pre-test programme was developed and executed. A part of the pre-testing was a full-scale trial casting executed under realistic circumstances. The result was in general very satisfactory. As an example Fig. 11 shows the result of an investigation of the concreting around the water stop forming a part of the full scale trial cast test item (a core has been drilled through concrete and water stop and a fluorescent epoxy impregnated plane section has been produced). It can clearly be seen how the concrete has completely surrounded the water stop and how the coarse aggregates are evenly distributed in the mix.

The actual casting of the closure joint roof slab was performed without any problems and the result - inspected from inside and outside (by divers) - was completely acceptable.

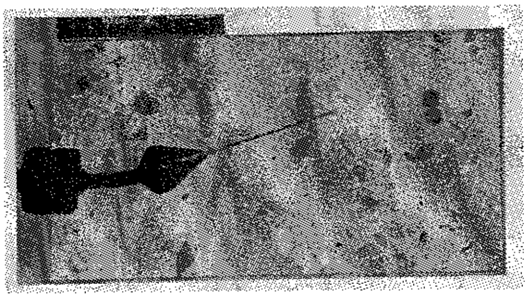


Figure 11 *Plane section from Full Scale Trial Casting showing complete casting-in of waterstop [4]*

MISCELLANEOUS

- **ACCIDENTS AND UNEXPECTED PROBLEMS**

Element # 13 sank during lowering [5, 8]
Early one summer morning during the lowering of yet another tunnel element the element suddenly sank the last 1.5 m within 20 seconds because the steel bulkhead gave way. It seemed ominous that this should happen to element # 13 (in fact, people among the contractors staff had tried to renumber it # 12A in advance), but the subsequent investigation showed that it might have happened to any of the previous elements.

The accident was caused by a combination of design, execution and inspection errors concerning the reinforced concrete sill beam at the bottom of the element supporting the bulkhead. The beam sheared off due to missing hairpin reinforcement.

At the time the incident occurred the inrush of sea water along the 175 m long element resulted in a 30 m high fountain of water coming out of the hollow tubular control tower on the element. Fortunately, the crew on top did not obey standard safety procedures and abandon the ship, because that would almost certainly have resulted in their death. In stead they stayed on board and one person actually kept calm enough to document the event by taking photos.

The element was inspected thoroughly by divers and in the end it was reclaimed, repaired and installed in the tunnel. Meanwhile construction of the tunnel continued from the other side of the tunnel.

D&R found 15 unexploded bombs in the sea bottom from the Second World War [7]
The British bombs were located along with an aeroplane and an aeroplane engine. The bombs were destroyed, but replicas were exhibited in the Øresund Exibition Center at Kastrup.

D&R found rocks weighing up to 100 Ton [7]
Two huge rocks, one weighing over 100 t, stand side by side on the artificial peninsula at Kastrup, looking as though someone forgot to remove them. The largest rocks removed during the D&R works, they represent the logo of the Øresund Region, symbolising the Danish island Zealand and the Swedish province Scania.

The bucket dredger sank [7]
One of the mainstays of the D&R works, the world's largest bucket dredger Chicago, capsized and sank in 1997 in the North Sea some 80 km off the Danish coast while being towed to Spain. It had been working in Øresund, mainly on the relocated Flinttrännen navigation channel. Luckily nobody was injured.

- **SAFETY AT WORK [10]**

Øresundskonsortiet and its two owners have operated a joint Safety at Work campaign, which involved everyone. The aim has been to develop a common culture of safety throughout the project, through a variety of different means.

Safety guidelines were prepared before issuing tenders. Instructional material and course training was provided free of charge by Øresundskonsortiet, and advisory pamphlets were issued to all workers. A newsletter was published four times a year and was widely read.

However, one of the chief boosts to the campaign was the introduction of a Safety at Work Award. Each site was regularly inspected and awarded points. Every six months an award was presented. As a result accident frequency dropped to a figure half that of the average for the building industry in the area. All the workers on the winning site shared the money, but in fact they often donated it to charity.

However, one fatality and two unexplained cases of seamen drowning were recorded. At the peak of the project almost 6,000 workmen were present on site. Altogether over the five years of the project just under 7,000 hours were lost out of a total of almost 3.6 million.

- **FIRE PROTECTION MEASURES [11]**

A major feature of the safety concept of the tunnel is a central gallery between the motorway tubes, which serves as a safe and smoke-free escape route in case of emergency.

The outer tunnel walls, the roofs and the upper part of the internal walls of the four traffic tubes are covered with fireproof insulation material. Fire protection of the joints in the tunnel is also provided.

The fire insulation material provides protection for minimum two hours against a hydrocarbon fire peaking at 1350 °C after one hour. The adopted material is Fendolite MII applied by spraying to a minimum thickness of 26 mm. Fendolite MII is a proprietary cementitious material with vermiculite aggregate.

- **RAILWAY SYSTEM [9]**

The socalled OTUs (Øresund Train Units) can operate in both countries independently of the technological differences in the Danish and Swedish rail systems, and are intended as a rapid mass transit system across relatively short distances.

The Øresund line is a double track electrified railway and trains run at speeds of up to 200 km/hr, freight trains 120 km/hr. The maximum gradient is 1.56 %. The track is ballasted, except in the immersed tunnel to save construction height.

The track width is the only similarity between the Danish and the Swedish rail systems. The power supply to the Danish and Swedish railways has different voltages; the switch is made at an 800 m neutral section on Peberholm. In Sweden trains mainly run on the left hand track, whereas in Denmark trains normally run on the right, and there are also subtle differences in the interpretation of visual signals.

An automatic train control system (ATC) transmits data from the signal system to the train.

HAPPY END?

In spite of the tight time schedule and the various mishaps listed above the Link was completed before time.

Overall the Øresund project has received DKK 1,430 million in subsidies. The funds, for instance, have enabled Øresundskonsortiet to offer a bonus to the contractors of the project for completing their contracts on time – a contributory factor behind the smooth cooperation between the individual contractors.

The intermittent period between handing over and opening was used for various purposes: training of the Danish and Swedish railway personnel in operation of the system, commissioning of the surveillance and toll systems, emergency and rescue operation trials, but also:

- **FUN RUNS**

In aid of charity Red Cross were allowed a four-day festival for the public including e.g. inline skating races, half marathon runs, professional bicycle races and family outings. Over 79,000 people participated in the half marathon run; the men's winner came from Ethiopia, taking 59.46 min. The women's winner came from Tanzania, taking 1hr 7 min and 55 sec. The inline skating event was billed as the largest inline race in the world with a maximum limit of 25,000 skaters.

- **THE GRAND OPENING**

The Grand Opening occurred on 1 July 2000, three months before originally scheduled, in the presence of the Swedish King and the Danish Queen plus the two prime ministers and a large number of other officials. Several thousand of the various personnel having contributed to the construction of the Link were also invited. The ceremony was transmitted on Danish and Swedish national TV and radio as well as all over the world.

The project was completed without any outstanding litigation, which seems to be unusual nowadays.

- **OPERATION**

The predicted number of 11,000 vehicles per day has not been met, however. After the first year's operation the road traffic is still 15 – 20 % less than predicted. A total of 2.9 million cars have crossed the Link carrying a total of 8 million passengers driving a total of 47 million km.

The railway passenger numbers have exceeded the most optimistic forecasts. The Danish Railway System (DSB) has during the first year's operation sold 1.2 million tickets more than predicted. The total number of passengers has been 5 million.

The car ferries between Helsingør and Helsingborg, approximately 50 km north of the Link, have continued operation and seem to be favoured especially by the heavy vehicles. Their market share is 75% of the lorry traffic, 50% of the bus traffic and 40% of the car traffic.

The passenger ferries between Copenhagen and Malmö have also continued operation (although one of the two companies has closed), but have lost more than 1.7 million passengers, reduced the number of crossings from 15.000 to 10.000 per year and sold four of their vessels.

The hovercraft ferry service between the Kastrup airport and Malmö has been discontinued.

REFERENCES

1. Jacobsen, T.: *"Paying for the link"*, The Øresund Fixed Link, special publication by Route One Publishing Ltd. (UK), 2000, p. 16-17.
2. Lundhus, P. & Braestrup, M., *"The Øresund Fixed Link - Øresundsbron"*, Structural Concrete, Vol. 1, No. 2, June 2000, p. 65 - 70.
3. Lundhus, P., Braestrup, M. & Falbe-Hansen, K., *"The Øresund fixed link between Denmark and Sweden"*, New Technologies in Structural Engineering, IABSE/FIP International Conference, 2-5 July 1997, Lisbon, Proc. Vol. 2, p. 1187 - 1201.
4. Henriksen, H., Kjaer, U. & Lundberg, L., *"Concrete technology. Development of concrete mixes for tunnel elements and ramps and experiences from the concrete production and castings"*, Øresund Link immersed tunnel conference, 5-7 April 2000, Copenhagen, p. D1-1 – D1-12.
5. Nilsson, L.-G., Brandsen, C., Lunniss, R. & Lambregts, H., *"Tunnel element 13. A successful turnaround – from disaster to success"*, Øresund Link immersed tunnel conference, 5-7 April 2000, Copenhagen, p. D10-1 – D10-10.
6. Russell, H., *"Achieving the ultimate goal"*, The Øresund Fixed Link, special publication by Route One Publishing Ltd. (UK), 2000, p. 19-20.
7. Smith, P., *"The big dig"*, The Øresund Fixed Link, special publication by Route One Publishing Ltd. (UK), 2000, p 33-38.
8. Smith, P., *"Tunnel under Drogden"*, The Øresund Fixed Link, special publication

by Route One Publishing Ltd. (UK), 2000, p. 41-36.
9. *"One system, two railways"*, The Øresund Fixed Link, special publication by Route One Publishing Ltd. (UK), 2000, p. 65.
10. Monro, M., *"A common culture"*, The Øresund Fixed Link, special publication by Route One Publishing Ltd. (UK), 2000, p. 69.
11. Skotting, E. & Braestrup, M., *"Operational traffic safety and fire protection measures"*, Øresund Link immersed tunnel conference, 5-7 April 2000, Copenhagen, p. E2-1 – E2-6.