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Some Durability Considerations in the Design of the Confederation Bridge

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Synopsis: Transportation to and from Prince Edward Island, Canada's smallest province, has been by ferry for the past century. The cost to operate the ferry system became an increasing burden for the Canadian government and a proposal call was solicited in 1987 to the private sector to construct and operate an alternate system to the Province of Prince Edward Island. A proposal was accepted for a private consortium to build a 12.9 km bridge from the mainland to Prince Edward Island. The bridge was completed in May, 1997.

A precast concrete, post-tensioned segmental box girder structure was selected for the site. A requirement of the Government of Canada was that the design and construction of the bridge provide a structure with a design life of 100 years. The bridge is located in a harsh marine environment, with some 100 annual cycles of freezing and thawing. Ice floes which originate in Northern waters pass through the Northumberland Strait in the winter and early spring months. Water temperatures vary from about -2 °C in the winter months to +18 °C in summer. The salinity of the water in the Northumberland Strait is approximately 3.5%.

This paper presents some of the durability concerns which were considered during the design and construction of the bridge and describes how these concerns were addressed.

Keywords: abrasion; aggregates; alkalies; chlorides; curing; durability; fly ash; freeze thaw durability; scaling; silica fume; sulphates.

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INTRODUCTION

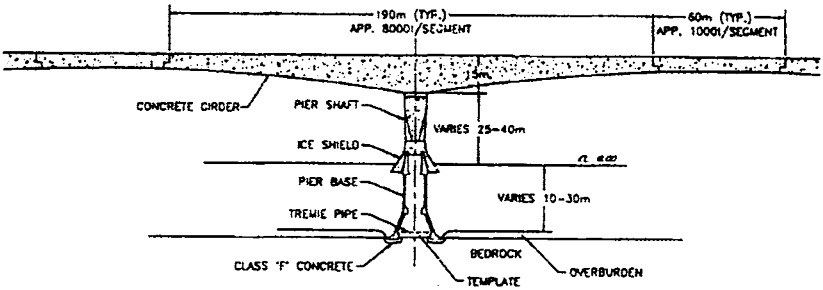
The Confederation Bridge completed in May 1997, across the Northumberland Strait, is a complex multi-span concrete box girder structure 12.9 km in length. It consists of multiple fixed frames separated by expansion joints and hinges so as to accommodate the movements associated with loading, creep, shrinkage and thermal effects. The structure is designed for a service life of 100 years in a harsh marine environment. Many design and construction features are specific to this structure. The piers for the main girders are founded in upwards of 35 meters of water and in current velocities approaching 2 meters per second, thus, accessibility for monitoring and repair of defects, if required, would be extremely difficult.

The approach section on Prince Edward Island (Canada's smallest province) consists of six spans of 93 meters each, founded on sandstone bedrock with shear keys to resist the lateral loads of wind, waves and ice. The west approach piers for the 14 spans of 93 meters each, are founded on vertical and battered, concrete filled pipe piles. The pier shafts were constructed of match cast segments which were post tensioned vertically in place. The bridge has a deck width of 11 meters which allows for one traffic lane and one wide shoulder in each direction. The bridge has a typical clearance of 49 meters above sea level with the exception of a navigation span which is 60 meters above water. The main bridge girders were segmentally constructed as well, using a balanced cantilever method.

The main bridge consists of 44 spans of 250 meters each. The piers for the main spans were cast on land in the Prince Edward Island staging facility, moved to a jetty by an innovative hydraulic slider technique, and then transported to the site by a heavy lift marine vessel. These piers were located on three previously installed concrete positioning pads, and further supported by tremie concrete between the pier base and bedrock.

The main span girders were match cast and post tensioned at the staging facility and then transported to the site. The spans were constructed using two types of components: a 190 meter cantilever unit and a 60 meter drop-in span. The completed cantilever units weigh upwards of 8000 tonnes. The cantilever girder depth varied from 14.5 meters at the piers to 4.5 meters at the cantilever tip.

The location of the Confederation Bridge is shown in Fig. 1 and a typical pier foundation, pier shaft, main span girder and drop-in section is shown in the sketch below.



The Confederation Bridge crosses the Northumberland Strait from the mainland of Canada to Canada's smallest province, Prince Edward Island. The placid summer waters of the strait, reverts to a cold hostile marine environment in winter and early spring, as the Gulf ice moves through the strait. This places a high demand on the quality of concrete materials, production and construction. Development of ice in the strait is of little consequence compared to the affects of tide and wind driven ridged and rafted ice. The size and configuration of the bridge pier foundations are largely dependent on the imposed ice loads. The design utilizes an ice breaking cone at water level to reduce the imposed loads by causing the ice to bend upward and break in flexure. This cone or ice shield is either clad in cathodically protected steel or constructed of very high strength concrete for improved abrasion resistance.

DURABILITY OF CONCRETE

High durability is not an intrinsic property of concrete, but is achieved by a judicious choice of materials, accurate proportioning, thorough mixing, proper placing, adequate curing and protection. The main force of deterioration was considered to be that of chloride ingress and subsequent corrosion of the reinforcing steel. Other potential deterioration forces considered were alkali-aggregate reaction, sulphate attack, freezing and thawing, ice abrasion, salt scaling and cracking due to thermal gradients if these were not controlled within tolerable limits.

The approach taken to address the durability concerns are addressed in the following subsections.

Concrete Materials

Cement - A low alkali, silica fume blended cement was used throughout all concrete manufacture. This particular cement was manufactured to strict specifications for this particular project. Approximately 130,000 tonnes of the cement were utilized.

The low alkali cement, blended with 7.5 percent silica fume was required to contain a tricalcium aluminate content between six and ten percent. This range was considered appropriate for the marine environment such that neither depassivation of the reinforcement steel or potential for sulphate attack should occur.

Fly Ash - A low calcium fly ash (ASTM Class F) was used in most of the structural concrete at 15 percent replacement by mass of the blended cement. The fly ash was found to have a beneficial affect on heat development, permeability, concrete workability and air void stability. The fly ash replacement was in the order of 29 percent in the more massive sections of the structural components, so as to minimize the potential for thermal cracking.

The properties of the silica fume blended portland cement and fly ash are shown in Table 1.

Aggregate - Aggregate comprises some 70 percent by volume of high performance concrete; thus, the long term stability of the fine and coarse aggregate is a significant factor, particularly for the 100 year design life.

Twelve sources of sand and gravel were identified in Atlantic Canada and Quebec as potential sources of concrete aggregate for the Confederation Bridge. Extensive petrographic examinations were performed so as to identify potential long term problems such as alkali-aggregate reaction, presence of pyrite, poor crystal structure, high porosity, etc. Coarse aggregate, processed from a fine grained granitic intrusion was selected for the coarse aggregate and a natural quartz sand was selected for the fine aggregate. These materials were processed, washed and classified at the source and the coarse aggregate was further washed on site after shipment and immediately prior to batching concrete.

The results of the alkali-aggregate reactivity tests are shown in Fig. 2 and 3. The expansion measured on the aggregate was well below the acceptable limit of 0.1 percent in the accelerated mortar bar test and 0.04 percent in the concrete prism test at 24 months.

Concrete Mixtures

Approximately 360,000 cubic meters of concrete was used in the construction of the Confederation Bridge. The concrete for the various phases of construction could be divided into four basic classes as follows:

Class A	Structural concrete for main girders, drop-in spans, pier shafts, pier bases and abutments.
Class A100	Exposed ice shield concrete.
Class C	Approach pier foundation and mass concrete (concrete sections greater than one meter in thickness).
Class F	Tremie structural concrete (antiwashout admixture used in moving water).

Each of the classes of concrete (with the exception of the tremie concrete) was available with either a 20 mm or 10 mm nominal maximum size of coarse aggregate, and their usage depended on the congestion of reinforcement and clear space in the formwork.

Class A Concrete - The requirements of the Class A concrete were as follows:

Minimum cement content	450 kg/m^3
Maximum water/cementitious materials	0.34
Maximum Rapid Chloride Permeability	1000 coul.
Maximum Water Permeability @ 28 days (CANMET Method)	10^{-14} cm/sec
Maximum air void spacing factor	260 µm
Average air void spacing factor	< 230 µm
Design strength @ 91 days	60 MPa

The mixture proportions of the Class A concrete are shown in Table 2. It may be noted that the requirements for low permeability and low water-cementitious materials ratio override the requirements for strength. Table 3 provides physical properties of the Class A concrete as developed in the laboratory.

Class A 100 concrete - A special high performance concrete was developed for the pier shaft ice shields. The ice which moves through the Northumberland Strait during the late winter and early spring contains abrasive sediments picked up during grounding of the ice floes.

Table 2 shows the concrete mixture proportions for the Class A100 concrete.

The concrete used in the ice shields had a very low water cementing materials ratio of 0.25, which provided a Rapid Chloride Permeability of 125 coulombs at 91 days. The average compressive strength of the A100 concrete mixture used in the ice shield was in excess of 80 MPa at 91 days. The abrasion wear was approximately 60 percent of that of the 80 MPa concrete (Class A). Fig. 4 shows the results of the surface abrasion test for various concretes using the ball bearing method as outlined in ASTM.

Class C Concrete - The requirement to maintain a thermal differential of less than 20 °C within the concrete and a maximum temperature in mass concrete of less than 70 °C was controlled by the use of a low calcium fly ash, substituted for 30 percent by mass of the total cementitious materials. The fly ash was batched as a separate ingredient at the batch plant. The tertiary blend of low alkali portland cement, silica fume and fly ash gave excellent performance and imparted a very low permeability to the concrete.

The requirements for Class C concrete were as follows:

Minimum cement content	300 kg/m^3
Maximum fly ash content	130 kg/m^3
Maximum water/cementitious materials	0.36
Maximum air void spacing factor	260 µm
Average air void spacing factor	< 230 µm
Minimum compressive strength @ 91 days	40 MPa

Table 2 shows the mixture proportions for the Class C concrete.

Class F concrete - Class F concrete was used for tremie placement in shear keys, tremie seals, and beneath the precast pier foundations as a support for the bridge piers on the sandstone bedrock. The tremie concrete was placed in a variety of conditions dictated by the environmental conditions in the Northumberland Strait. While some of the pier bases were placed in relatively quiet water, others were placed in water currents upwards of two meters per second. Design criteria for the Class F concrete has been adopted largely from the Japanese standards and codes. The tremie concrete was placed in upwards of 35 meters of water, under diver surveillance.

The following requirements were applicable to the Class F concrete:

Minimum compressive strength	35 MPa @ 28 days
Slump flow	475 - 550 mm
Air content	4 - 7 %
Washout CRD test	10 % maximum
Slump (without antiwashout)	180 ± mm

The slump flow test is the measurement of the flow in mm of the diameter of the concrete after performing the standard slump test.

Table 2 shows the concrete mixture proportions for Class F concrete in quiet water without antiwashout admixtures and for use in flowing water with antiwashout admixtures.

Air Content and Slump

Air Content - The requirements for air content, spacing factor and specific surface were as outlined in CSA A23.1-1994. The requirements were as follows:

Total air content		5 - 8 percent (plastic concrete)
Spacing factor	Average	230 μm
	Maximum	260 μm
Specific surface		$\geq 23.6\ mm^{-1}$

The total air content of 5 - 8 percent was used as a guide only and concrete acceptance was based on either a satisfactory air void system in the hardened concrete or a RDF in excess of 70 percent after 500 cycles in the ASTM C666 Procedure A test.

The structural concrete had a specified slump of 180 ± 40 mm. The pumpline configuration varied widely to accommodate all the various placing scenarios. The length of pumpline and free fall in the downline had a marked influence on air loss through the pump and resulting air void spacing factor.

Table 4 shows typical results of air measurements after mixing, prior to pumping, after pumping and after vibration in the formwork in mock-up tests. The tests are not indicative of the concrete in the structure but indicate the necessity to carefully plan the placement methodology.

Mixing time also had an influence on the quality of the air void system and Fig. 4 shows the relationship between mixing time and air void spacing factor for a concrete mixture with 7.5 percent air.

Freezing and thawing tests on field samples cut from mock-up structural elements, indicated that the high performance concrete would pass the ASTM C666 test with a spacing factor in excess of 300 μm. A spacing factor up to 300 μm was accepted in areas where critical saturation was unlikely to occur. This would exclude the tidal zone or splash zone.

Chloride Ingress

Corrosion of the reinforcement steel is recognized as the primary factor leading to deterioration of air entrained concrete. The chloride ion destroys the natural passivating layer of iron oxide that forms around the embedded reinforcement and then acts as a catalyst in the steel corrosion process. The rate at which corrosion continues is governed by the access to water and oxygen, electrical resistivity of the concrete and other geometric factors. There is no general agreement of the level of chloride ion required to be present, such that corrosion will be initiated. The stated limits generally vary from 0.4 to 0.5 percent by mass of cement. Many current codes define the upper chloride threshold level in terms of cement content and 0.4 percent of the cement mass is commonly stated.

The corrosion threshold for prestressing steel is considered to be less than that for reinforcing steel, and the critical levels are often stated as 0.1 to 0.2 percent by mass of cement.

A very low permeability concrete is assumed to be the best defense against the ingress of corrosive ions. This assumes a high quality covercrete. The relative permeability of the concrete was determined by the Rapid Chloride Permeability Test, steady state diffusivity testing, water permeability tests and chloride ponding tests. There was a good general agreement in these tests in that all tests values were very low.

In predicting the service life based on a threshold level of chloride ion in concentration at the reinforcement, Fick's Second Law of Diffusion was utilized. The time to threshold corrosion levels were predicted based on a diffusion coefficient of $4.8 \times 10^{-12} m^2/sec$, a chloride concentration of 2100 ppm (measured in the Northumberland Strait) and a cover thickness of 75 mm. Based on these assumptions, a threshold level of chlorides will not be present for 60 years.

The predicted years to corrosion is considered to be conservative since:

a) the Cl^- binding capacity of silica fume has not been considered
b) the chloride diffusivity of concrete is known to improve with age - actual measurements have shown an improvement by a factor of 10.
c) the prediction was performed for cement only concrete
d) the high resistivity measured in the actual concrete (500 ohm-m) should extend the time to corrosion by 20 to 30 years.

Concrete will still have useful life after the threshold level of chlorides are reached. Timely maintenance will ensure continued service.

Alkali-Aggregate Reactivity

Many of the aggregate sources in Eastern Canada are alkali-silica reactive. The low calcium fly ash used in the Confederation Bridge concrete has been used for approximately 12 years as a method to ameliorate alkali-silica reactivity. This particular source of fly ash has been researched thoroughly since the 1980's and has proven to be a reliable source.

Silica fume also ameliorates the expansions which accompanies alkali-silica reaction (in the short term at least). The quantity of the silica fume in the blend of low alkali portland cement, silica fume and fly ash (5.3 % to 6.4 %) would not be sufficient to control expansion with the use of a reactive aggregate. The important nature of this structure and the design for a long service life of 100 years dictated that a non-reactive aggregate be used as well as a low alkali cement and supplementary cementing materials.

Sulphate Attack

Normal portland cement (CSA Type 10) commonly used in marine construction in Eastern Canada contains a C_3A content of 11to 13 percent. Historically, this cement has performed well in the relatively cold waters of the Atlantic ocean, and there is no recorded serious sulphate damage to marine structures , even though some of these structures are in excess of 70 years old. It is believed that by specifying a C_3A content of from 6 to 10 percent and with the low permeability of the concrete, that sulphate attack will not be a concern in the 100 year service life. The usage of low calcium fly ash further reduces the potential for sulphate deterioration.

Freezing and Thawing Resistance

Concrete is generally considered to be resistant to cyclic freezing and thawing in a saturated condition, if the air void spacing factors are less than about 230 µm and the specific surface greater than 23.5 mm^{-1}. The spacing factor is the more important and may be the controlling factor in durability. Concrete in the Confederation Bridge which is considered to be in a highly susceptible environment for freezing and thawing damage to occur, includes the ice shields in the tidal zone, the elevation to which wave run-up occurs on the pier shafts and the bridge deck, including the barrier walls.

Flowing concrete (slump 180 mm to 240 mm) containing silica fume, a high cement factor and superplasticizer is difficult to place while maintaining proper air void characteristics. Air losses occur during extended mixing and transport, pumping, placing and vibration. There is a tendency for the air void spacing factor to increase from the time of mixing to the end of placement.

The pump line configuration appears to be a major factor in air losses and changes in the air void parameters. It is postulated that very small air bubbles go into solution in the concrete mixture water during pumping and further that significant air is lost through vacuum extraction in pump down lines. The height of the pump boom must be kept at a minimum to avoid undue air losses.

Table 4 shows the air losses and changes which can occur in the air content and air void system from the time of mixing to the time of placement.

Some researchers have indicated that the air void spacing factor may be increased for high strength concrete of low water cementing materials ratio. There is insufficient data related to field performance of high strength concrete in an aggressive marine environment to consider an increased air void spacing factor at this time for other than portions of the structure which is unlikely to be critically saturated.

Ice Abrasion

During the winter and early spring, ice floes move through the Northumberland Strait, and make contact with the pier ice shields. The ice shields are sloped 52° so that the moving ice will move up the slope, fail in flexure and pass around the piers. This reduces both the horizontal ice pressures on the piers and reduces surface abrasion. The zone of contact between the ice and the ice shield is approximately from elevation -1.3 m to +3.0 m.

Some of the moving ice carries embedded sand and gravel picked up during grounding of the ice on the shoreline. The embedment of granular material causes additional abrasive action on the concrete.

An air entrained concrete mixture (mixture A 100 described earlier) with a compressive strength of 80 MPa and water cementitious materials ratio of 0.25 was used in construction of the ice shields. Abrasion resistance is known to be highly dependent on compressive strength. The interior of the formwork for the ice shield concrete was covered with a controlled permeability form liner so as to provide a dense and smooth surface on the concrete.

Fig. 5 shows a comparison of 60 and 80 MPa concrete with and without the form liner as well as the abrasion resistance of normal structural concrete with a compressive strength of 35 MPa. The high quality concrete in the ice shield should provide serviceability for the design life.