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Concrete Specifications for the Øresund Link

Spécifications du béton pour la liaison d'Øresund

Beschreibung der Betonsorten für die Øresund-Verbindung

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SUMMARY

The construction of the Øresund Link between Denmark and Sweden involves, in addition to the sea crossing, several land-based concrete structures (bridges, tunnels etc.). These structures involve costs of approx. 800 million USD. A service life 100 years has been specified for these structures. To avoid that the individual consulting engineers spend unnecessary time and money in order to develop improved concrete specifications, the Owner has produced a guideline for the selection of concrete. The technical background of the specifications is described.

RÉSUMÉ

Outre la traversée proprement dite, la liaison d'Øresund entre le Danemark et la Suède comprend plusieurs constructions en béton tels que ponts, tunnels, etc. Ces constructions coûteront environ 800 million USD. La durée de vie de ces constructions a été spécifiée à 100 ans. Afin d'éviter que les ingénieurs conseils ne perdent du temps et de l'argent à développer des spécifications améliorées pour le béton, le maître de l'ouvrage a élaboré une directive pour la sélection du béton. Une description de la base technique des spécifications est donnée.

ZUSAMMENFASSUNG

Der Bau der Øresund-Verbindung zwischen Dänemark und Schweden umfasst neben der Verbindung von Küste zu Küste auch mehrere Festland-Betonkonstruktionen, wie z.B. Brücken, Tunnels, usw. Diese Konstruktionen sind mit Baukosten in Höhe von USD 800 Mio. verbunden und sind für eine Nutzungsdauer von 100 Jahren ausgelegt. Damit die beratenden Ingenieure keine unnötige Zeit für die Entwicklung von verbesserten Beton-sorten verbringen, hat der Bauherr, eine Anweisung zur Wahl der Betonsorte erarbeitet. Es wird der technische Hintergrund der Betonbeschreibung erläutert.

1. BACKGROUND FOR THE SELECTION OF THE CONCRETE TYPE/MIX DESIGN

The Øresund on-shore works on the Danish side comprise primarily of traditional bridge structures. There is extensive experience with design and execution of such bridge structures in Denmark, in accordance with the Danish Road Directorate's General Specification (AAB). Experience gained over a period of 50 years has shown that design and execution in accordance with these specifications generally results in sound and durable bridge structures. However, for certain severely exposed structural elements, experience shows considerably reduced durability when compared with the rest of the structure. The reason for reduced durability is usually design and/or execution errors which lead to unforeseen rapid development of damage by corrosion, frost and/or alkali silica reactions.

Based on this the concrete was to be selected according to the following overall requirements:

1) The choice of the concrete must be made in consideration of minimizing the risk of execution problems when placing the concrete.
2) The choice of the concrete mix-design, especially the water-cement ratio and the inclusion of additives, should secure a concrete with optimum workability and hence a satisfactory quality of the works.

Consequently, the specifications must reflect a number of individual considerations by the individual consulting engineer in order to achieve the optimum design and to ensure that the requirements can be handled later by both the contractor and the supervision.

2. SERVICE LIFE CALCULATIONS

2.1 Technical background

As stated in section 1 experience has shown that earlier standard specifications have to be tightened.

In order not to specify unrealistic demands or demands based on only assumptions it was decided to perform service life calculations.

The background for the service life calculations was an investigation made by the Danish Road Directorate in 1990 [2] to evaluate the cause and extent of the found damage to concrete bridges of the Danish highway network.

2.2 Specification of service life

The service life of a structure may be defined as one of four different time periods illustrated at figure 1.

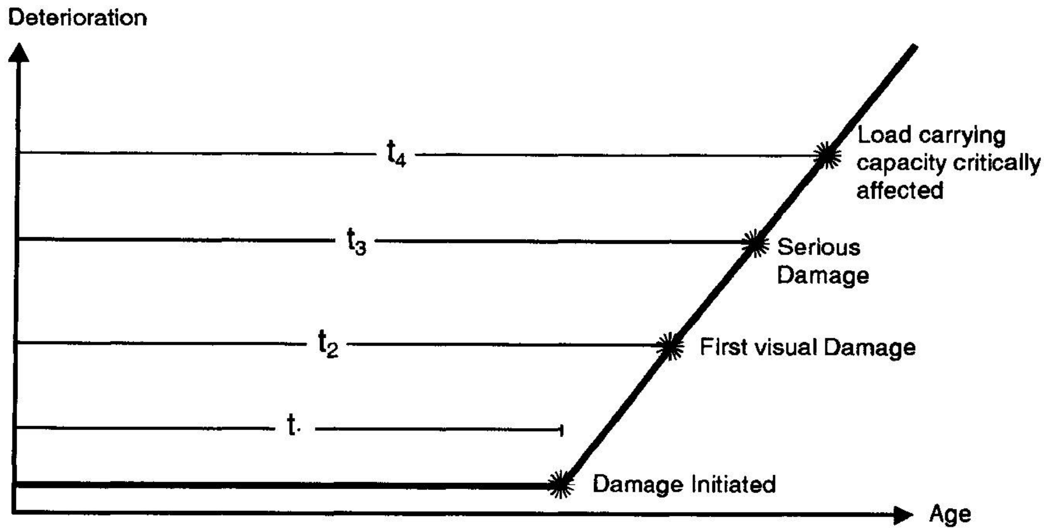

Figure 1: The figure illustrates the deterioration of concrete as a function of time.

Time periods t_2 and t_3 apply to this project and are defined in the following.

The requirement for the operation period for the structures, t_3, is a minimum of 100 years.

The requirement for the period t_2 is a minimum of 50 years. In this period the concrete must remain without damage and must be maintenance free except for maintenance of measures to extend the service life, e.g. a membrane on a bridge deck. Minor concrete repairs will be accepted after 50 years.

2.3 Calculation of service life, choise of environmental class

Corrosion caused by chloride ingress is considered to be the prime deterioration mechanism. Alkali silica reactions and freeze/thaw damage are other deterioration mechanisms. However there is extensive experience how to prevent them. So they are not considered to be problematic.

The service life of a concrete structure placed in chloride-contaminated environment can be calculated using Fick's 2nd law, as shown in figure 2. The values of surface chloride concentration C_s (0,1% and 0,2% mass of dry concrete) are based on the experience described in section 2.1 and [2]. The used values of the diffusion coefficient D are calculated from the formula: $D = (w/c)^5 \cdot 5000$. The calculation of D from this formula is in accordance with experimentally found values of D [2] for w/c ratios 0,45. The critical chloride content C_{cr} is estimated to 0,05% mass of dry concrete [2].

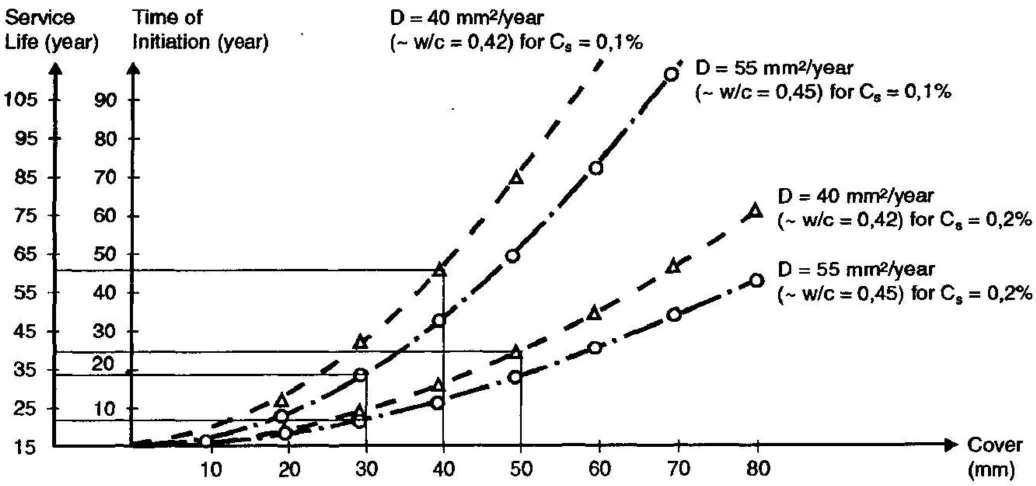

Figure 2 Theoretical time of initiation (t_1) and service life (t_2) as a function of D (diffusion coefficient) and cover for C_S = 0,2% and C_{cr} = 0,05%.

As a result of the calculations it was decided to use a w/c ratio of 0,42 (exist. requirements: 0,45) and a cover of 50 mm (exist. requirements: 30 mm) for structures in highly aggressive environment (C_s = 0,2%). A cover of 70 mm was specified for columns in sea-water, where C_s is estimated to 0,5%. For structures in a less aggressive environment (0,1%) a w/c ratio of 0,45 and a cover of 40 mm was required.

The decided parameters of 0,42 w/c ratio and 50 mm cover are seen to be theoretical insufficient to meet the requirement of 50 years of service life, before the first repairs can be accepted. However, a w/c ratio of 0,42 is within the limits of the concrete requirements that positively will meet the demand for a workable concrete to be cast without problems with a cover of 50 mm. Furthermore the requirement for sufficient drainage of traffic lanes will tend to place the structure in a less aggressive environment than the highly aggressive environment foreseen.

So the sound engineering judgement takes priority over the theoretical calculations based on which only even more tightened requirements should have been chosen with the consequence of increasing the risk of execution errors.

2.4 Accuracy

The evaluation of service life discussed above is, to a large extent, based on diffusion models from the laboratory and on parameter values which in practice are uncertain. Concerning the diffusion model used, experience has shown that values measured in practice are close to the theoretically calculated curve. However, the data is limited since it is based either on laboratory experiments or on data collected from existing structures of approximately same age (20-30 years). The general validity of the model for use in long term forecasts is therefore not demonstrated in practice. However, at the moment it is the only model which can be used in evaluation of service life.

Consequently, use of the model is acceptable provided due consideration is given to the uncertainties mentioned and that the model and the results are used only as a general guideline for the choice of concrete cover and w/c ratio respectively.

The calculated service life is considered to be on the safe side since the calculations do not take positive effects known from laboratory experiments into account.

3. MEASURES TO PROLONGE THE SERVICE LIFE

It is important to ensure that all elements of a completed structure achieve the same service life. It is therefore important to evaluate the future needs of repair and maintenance related to each structure. It may so be relevant to evaluate (technically and economically) the need for measures to prolonge the service life in order to avoid repeated repairs of the concrete as shown in the following example.

EXAMPLE:

In order to avoid repairs to columns in year 50 the recommendation could be the use of stirrups and main reinforcement of stainless steel. The extra cost of using stainless steel is per column about 1,000.- US $.

If only stainless steel stirrups are used the extra cost per column is about 110.- US $.

The cost of concrete repairs is 4,000.- US $ in 50 years and 8,000.- US $ in 75 years respectively.

The comparison between costs (in US $) is shown below:

Year	Mild steel	Stainless steel	Stainless stirrups
0		1,000	110
50	4,000		
75			8,000
Net present value*	600	1,000	550

* Discount rate 4%

From the example it is seen that an investment in stainless steel main reinforcement is not beneficial, but the use of stainless steel stirrups should be considered.

4. FINAL REMARKS

At the present time and with the present limited understanding of concrete technology the observed durability problems with some structures, dominate any discussion concerning concrete as a building material.

As a consequence, this might lead in the future to unrealistic requirements for concrete as the limited laboratory based experience, appears to call for tightening of the specifications. Especially even tighter requirements for the w/c ratio and the use of pozzolans to arrest chloride penetration has to be carefully considered. This is due to the fact that a reduction of the w/c ratio has resulted in an increased risk of execution problems which eliminates the theoretical benefits of a reduction in w/c ratio.

The evaluation of the choice of the concrete for the Øresund land-based structures has however, revealed that only minor changes to the existing requirements are needed to obtain remarkable benefits regarding prolongation of the expected service life without involving unacceptably high costs.

This is of course a prediction which can only be confirmed over time. The practical experience of 25 years of bridge maintenance in Denmark however supports the expectations.

With regards to the proposed concrete the experiences accumulated up till now on the Øresund Project with the use of the concrete show that it is workable and can be cast without problems and risk of honeycombs, cracks etc. The stress calculations which have been performed to avoid cracks due to temperature induced stresses and shrinkage can be problematic and have to be handle with care and a good understanding of the theoretical basis.

The results of the temperature/stress calculations have thus far proved to be realistic.

LIST OF REFERENCE:

[1] Guidelines for selection of concrete for Øresund On-shore works. A/S Øresundsforbindelsen 1992 and 1994.

[2] Chloride-induced Corrosion, (The Danish Road Directorate, October 1991)