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Issue No. 11 September/October 2000

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HIGH PERFORMANCE CONCRETE THE FLORIDA EXPERIENCE

Douglas L. Edwards, Federal Highway Administration

The era of high performance concrete (HPC) in Florida bridges actually began following a violent storm in Tampa Bay in 1980. A freighter crashed into one of the main piers of the Sunshine Skyway Bridge, causing collapse of a truss span and the deaths of 35 people. The replacement bridge, opened in 1987 and built in the corrosive waters of Tampa Bay, required more than 221,000 cu yd (169,000 cu m) of concrete. This project marked a turning point with respect to the use of high-quality concrete by the Florida Department of Transportation (FDOT).

During the 1970s, the FDOT became increasingly aware of structural concrete deterioration, especially along Florida's 1200 miles (1930 km) of coastline and intra-coastal waterways. In response, FDOT undertook to define areas with environments of similar corrosive aggressiveness within the State. In 1981, this effort resulted in the publication of "Corrosion Maps" showing three levels of environmental aggressiveness based upon criteria for pH value, resistivity, sulfate concentration, and chloride concentration.

Much concrete research was conducted by the FDOT during the 1970s. This research indicated that the addition of fly ash benefited a concrete structure in three ways:

- Improved corrosion protection
- Improved sulfate resistance
- Reduced heat of hydration

When the new Skyway Bridge was being planned, an expert board of concrete technology consultants was assembled to study the concrete durability problems in Tampa Bay. This group advised the State that all concrete used in the structure should contain fly ash. When the new bridge construction began in 1982, fly ash was officially required. This initiated an intensive effort in Florida to incorporate fly ash in structural concrete.

Following the Skyway project, FDOT began development of a standard concrete specification to incorporate many of the durability features utilized on this unique structure. During this period, corrosion was detected in the substructures of several relatively new bridges in the Florida Keys. These bridges were built with conventional concrete and epoxy-coated reinforcement. This created an urgent need for an alternative means of corrosion protection. A wide range of HPC mixtures was produced and tested to establish optimum mix designs for durability. This effort led to progressive refinements in the FDOT concrete construction specifications, corrosion classification parameters, and corrosion protection design procedures and requirements.

Since 1985, all proposed FDOT bridge sites have been required to have soil and/or water testing performed. One of three corrosion environments is then assigned to each bridge component. These environmental classifications then establish steel reinforcement cover, and in conjunction with strength requirements, the FDOT concrete class to be used. Moderate and extremely aggressive environments currently require the use of fly ash or ground granulated blast furnace slag with specified minimum concrete compressive strengths ranging from 5500 psi (38 MPa) to 8500 psi (59 MPa). Type II cement is specified for extremely aggressive environments. When this classification is due to chlorides in the water, calcium nitrite and silica fume are specified for specific structural elements. When silica fume is specified, the rapid chloride permeability is limited to a maximum value of 1000 coulombs. The FDOT corrosion specialists predict that these mixes will provide a minimum design life of 75 years in Florida's severe marine environments.

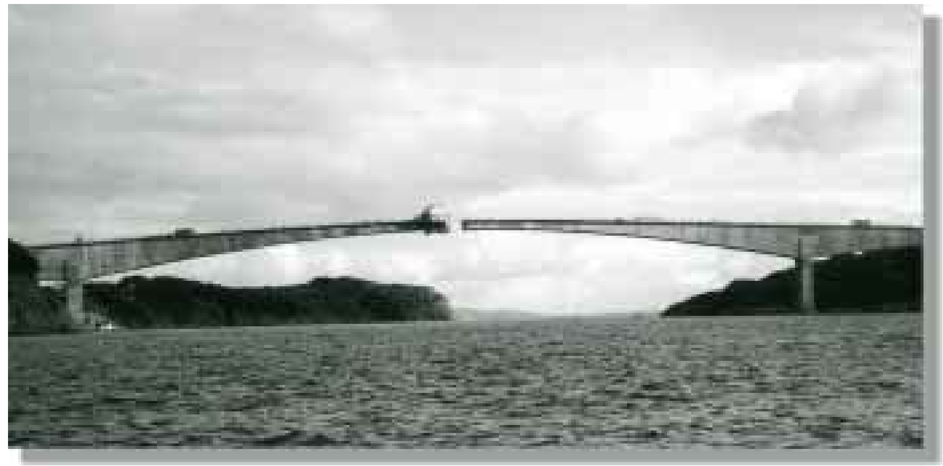
To date, the FDOT has focused its research on the durability aspects of HPC since this has a far greater economic impact on their program than increased strength. Research is providing a better understanding of the effects of cold joints and cracks on reinforcement corrosion. As greater knowledge is gained in the fields of concrete materials and admixtures, corrosion monitoring, and alternative corrosion protection methods, it is expected that Florida's HPC criteria will continue to evolve.

LIGHTWEIGHT AGGREGATE CONCRETE IN NORWEGIAN BRIDGES

Steinar Helland, Selmer AS - Skanska AB, Oslo, Norway

A main characteristic of Norway is its long coastline. During the last century, a vast number of marine concrete structures have been built to facilitate communications and transportation. Since the 1970s, the discovery of large oil and gas fields off the Norwegian coast created the need for a number of gravity based as well as floating concrete production platforms.

Like the rest of the world in the late 1970s, Norway faced the problem of chloride-induced corrosion in our marine infrastructure. A program was, therefore, started to improve concrete quality and to develop models enabling us to assess the performance of these structures. This development resulted in the introduction of high strength, high performance concrete (HSC/HPC). Consequently, we were able to include concrete with characteristic cube strengths up to 15,000 psi (105 MPa) in our design code in 1989. In the same year, the Norwegian Roads Administration introduced a requirement for a water-binder ratio of less than 0.40 combined with the use of silica fume on all their infrastructure projects.



HPC lightweight aggregate concrete was used to reduce the weight of the main span on the Stolma Bridge

Lightweight Aggregate Concrete In Bridges

To help bridge designers in their efforts to create optimum structures, the Norwegian concrete industry, in the mid 1980s, started to combine the technology of HSC/HPC with that of lightweight aggregate concrete (LWAC). The first pilot project, constructed in 1987, was a 49-ft (15-m) long pedestrian bridge built with LC-60—a lightweight concrete with a cube compressive strength of 8700 psi (60 MPa). Later, ten major bridges were built with this material in Norway. These comprised free cantilever, cable stayed, and pontoon bridges. The spans of the two latest free cantilever bridges—Raftsundet at 978 ft (298-m) and Stolma at 988 ft (301-m)—represent world records.[1]

The motivation for using LWAC for free cantilevers has been twofold. Firstly, the effect of reduced dead load is obvious. Secondly, the construction method requires a balanced load on both sides of the pylon during construction. This limits the choice of span lengths and the possibility of placing pylons according to the topography. However, by being able to adjust the material density of the cantilevers, the designer achieves greater freedom.

Two of the bridges represent the revitalisation of an old concept—the pontoon bridge. Bergsøysundet (1992) with its 3000 ft (914 m) length, and Nordhordland (1993) with its 4088 ft (1246-m) length used LWAC of LC-55 (8000 psi or 55 MPa) in a total of 17 pontoons.[2] Again, dead load was important for the buoyancy, but equally important was the need to reduce the draft of the pontoons. Environmental considerations strictly limited the impact to the tidal water in the fjords.

LWAC Qualities

The structures are designed with concrete characteristic cube strengths of 8000 and 8700 psi (55 and 69 MPa) and densities in the range of 119 to 122 lb/cu ft (1900 to 1950 kg/cu m). Aggregates are made from expanded clay or shale. The specified water-binder ratio requirements have been less than 0.40, while actual ratios have been as low as 0.33. Silica fume has been used in all structures. In contrast to the North American tradition, dry lightweight aggregate has generally been used.

Field Performance

During the last 15 years, extensive research has been carried out in Norway to verify the LWAC's performance in a marine environment. This research includes the development of a service life model and laboratory and field-exposed test specimens. Typically, a number of test elements have been cast at the bridge sites and exposed in the tidal and splash zones as a part of the construction project. The results have given us the confidence that LWAC will withstand the design life of more than 100 years with comfortable margins.[3]

Ten years ago, the Roads Administration was sceptical about the use of high strength LWAC without any proven field performance. Today, their attitude has changed and they regard this technology as mature and a natural choice in the repertoire of materials needed to optimize bridge design.[4]

Codes and Regulations

All the structures have been designed according to the Norwegian Standard NS 3473. This has been updated both for HSC and LWAC several times during the 1990s. However, standards covering the materials and construction aspects of LWAC were not updated. The projects have, therefore, been constructed according to special project specifications.

The situation is changing with the new set of joint European concrete standards.[5] The parts on materials and construction have now been revised. The LWAC provisions are the fruits of major research projects in Europe[6] and represent state-of-the-art technology.

Economy

LWAC has a higher unit price as delivered from the batching plant. Savings in concrete and reinforcement quantities must compensate for this. However, reduced foundation costs, increased buoyancy, or the opportunity to apply different design concepts dominate the economy. All the LWAC structures have undergone an economical analysis to justify the choice of material. A number of these analyses are described in Reference 7.

Conclusion

To maintain the use of concrete in bridge construction, the range of material combinations had to be broadened in the 1970s and 1980s. The introduction of higher strengths and better performance in marine and de-icing salt environments was the first step. The second step was to give the designer the possibility of combining these characteristics with the freedom to specify density. Without these quantum leaps in technology, concrete's leading position in this market would have been questionable.

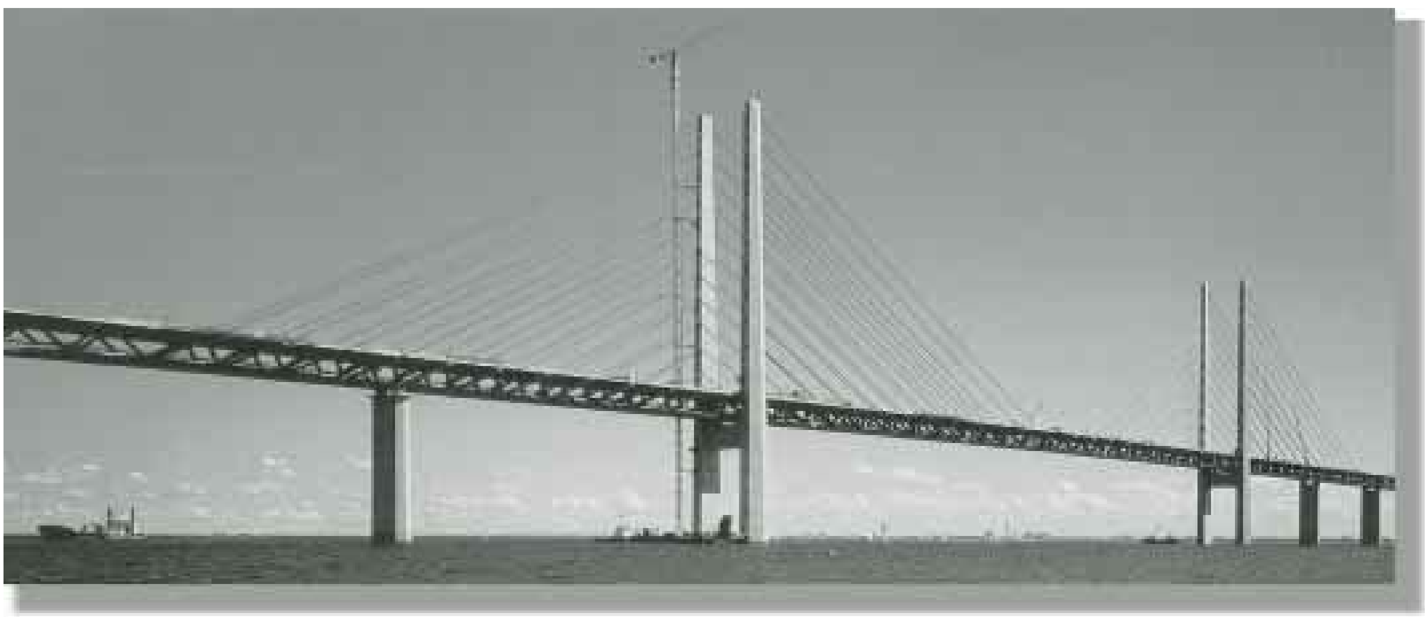
References

In June 2000, the Second International Symposium on Structural LWAC was held in Kristiansand, Norway. Ninety-six papers from more than 30 countries were presented. The proceedings are available from the Norwegian Concrete Association, www.betong.net.no. The following papers give more in-depth information on the subject of this article:

1. Rosseland, S. et al., "The Stolma Bridge—World Record of Free Cantilevering"
2. Jakobsen, S. E., "The Use of LWAC in the Pontoons of the Nordhordland Bridge, Norway"
3. Helland, S., "Service Life Modelling of Marine LWAC Structures"
4. Melby, K., "Use of High Strength LWAC in Norwegian Bridges"
5. Helland, S., "LWAC in the New European Standards on Materials and Execution"
6. Mijnsbergen, J. et al., "EuroLightCon – A Major European Research Project on LWAC"
7. Fergestad, S. et al., "The Economical Potential of LWAC in 4 Different Major Bridges"

THE ØRESUND LINK CONCRETE STRATEGY

Christian Munch-Petersen, Danish Technological Institute, Concrete Centre



A concrete strategy was adopted to ensure a 100-year service life

One of Scandinavia's largest investments in infrastructure—the Fixed Link across the Øresund Strait between Denmark and Sweden was opened on July 1, 2000. The link includes a two-track railway and a four-lane highway. The crossing consists of an immersed tunnel 2.2 miles (3.5 km) long, an artificial island 2.5 miles (4.1 km) long, a western approach bridge 1.3 miles (2.0 km) long, a cable-stayed high bridge 0.7 miles (1.1 km) long with a free span of 1608 ft (490 m), and an eastern approach bridge 2.3 miles (3.7 km) long. The immersed tunnel and the cable-stayed bridge are the largest of their types in the world carrying both road and rail traffic.

The Concrete Strategy

In 1994, the link's owner—Øresundskonsortiet—appointed an expert concrete group including specialists from the Danish Technological Institute and the Swedish Lund Institute of Technology. The group's first task was the development of the following strategy:

- Owner defines and controls concrete quality.
- Quality is defined by the requirements for concrete production including concrete mix proportions (Materials) and requirements for execution including curing (Workmanship).
- Quality is controlled by requirements for inspection, testing, and documentation as part of a quality system in accordance with EN ISO 9001.
- Requirements must be established by the owner and owner's consultants based on well-known technol-

ogy. The requirements must ensure a service life of 100 years with proper maintenance but without any major repair work. Corrosion of reinforcement is not permitted to start within the 100-year service life.

- Strategy is enforced through the preparation of a comprehensive concrete specification as part of the bid documents.
- Ensure open competition between contractors, without compromising quality.
- Specifications must leave as much freedom as possible for the contractors to choose concrete mix proportions, but thorough attention must be given to the risk of failing to obtain the defined quality.

The concrete had to meet high performance requirements. However, the term "high performance concrete" (HPC) is not used in Denmark. Requirements can be high or low, but performance can only be "yes" or "no." Therefore, per the Danish definition, there is no such thing as HPC. Nevertheless, in reality, concrete for the link would be described as HPC according to USA terminology.

Well-Known Technology

Well-known technology is defined as technology that is well tried with positive results under similar environmental conditions. Often, the owner would rather use well-known technology with the above definition than try a new (and maybe unsafe) technology in order to try to cut costs. When preparing the specification, questions about this principle arose. Which technologies are well-known and by whom? If the common and "well-known" technologies are regarded (and maybe proved by experience) as unsafe by experts, it may be sensible to use a new and—according to experts—safe technology. This is called an innovation.

The main innovations in the specifications were the use of:

- European constituent material standards
- Defined conformity procedures
- Stress calculations for early-age cracking
- Service life calculations including workmanship

Main Types of Concrete

The single crucial factor in the durability design of a concrete structure is the concrete cover to the reinforcement. The effectiveness of the cover depends on its thickness and the concrete quality. The concrete quality is primarily a function of the water-cement (w/c) ratio; therefore, durability design must include a minimum cover and a maximum w/c ratio. The specified values for the minimum cover and the maximum w/c ratio depend on the required service life and the aggressiveness of the environment, which again is somewhat dependent on the detailed geometric design of the structure and varies very much along the structure's surface.

It is sensible to define only a few different types of concrete with regard to w/c ratio. The thickness of the concrete cover can then be varied depending on required service life and aggressiveness of the environment. Thus, the total number of concrete types is reduced. For Øresund, only two types of concrete were defined:

- Type A with a maximum w/c ratio of 0.40
- Type B with a maximum w/c ratio of 0.45

Both types of concrete existed in a frost-resistant and a non-frost-resistant version and both types can be used with a cover of 2 or 3 in. (50 or 75 mm) depending on the environment. This way eight different environmental classes were addressed with only two concrete types. For all eight classes, the possibility of a 100-year service life was feasible.

Early-Age Crack Control

Temperature differences and autogeneous shrinkage can cause early-age cracking in the first few days of a structure's life. The requirements for early-age crack control are of great importance to the service life of a structure. Therefore, the Øresund requirements stated that the contractor had to calculate a cracking risk (P).

The calculation of P was performed using a finite element method. The input data were the variation of the properties of the hardened concrete with time and other data necessary to describe the contractors' planned execution, such as type of formwork, concrete temperature at placement, internal cooling system, and external insulation. The stresses calculated by the program were divided by the axial tensile strength of the concrete to give the cracking risk, P. The maximum acceptable risk of cracking (P) was specified as 0.7 for all water-retaining structures and splash zones and 1.0 or 1.3 for structures where some cracking is acceptable.

Frost Resistance

Guaranteed frost resistance was a must for the exposed structures. This was achieved through the selection of a concrete mix with an air-entrained system of high quality and stability. Through comprehensive pre-testing of the concrete, the necessary air contents were determined for the fresh and hardened concretes. The pre-testing included tests for salt-scaling and internal frost resistance. In production, only salt-scaling tests were made.

The Result

Defining a concrete strategy and following it has been a great success. The contractors were left with the possibility of deciding their own work procedure and concrete mixes while the quality was maintained because of the clear and strict specification. However, some problems arose where the contractor left out the air entrainment in some mixes or where the air content was too low. In these cases, the routine tests showed non-conformity of the mixes for frost resistance. No cracks have been found in the immersed tunnel. Some early-age cracks have been found in some of the structural elements. In all cases, the cracks were due to mistakes in the contractor's planning and execution. These were documented by calculation using actual construction data. Stress and strain analysis of the early-age cracking, therefore, gave a true picture of the cracking risk.

20 YEARS OF HPC BRIDGES IN FRANCE

*Didier Brazillier, BHP 2000 Project**

The first use of the term high performance concrete (HPC) in France goes back to 1983 and the building of a bridge at Melun under the impetus of LCPC and SETRA (Research Agency and Bridge Department of the French Highways Administration, respectively). This is not only of historical interest but is also highly significant in terms of the logic underlying the application of these types of concretes in France. Firstly, HPC relates to bridges rather than buildings. In France, there are few high-rise buildings and very little competition with steel construction in this sector. Secondly, bridge ownership or sponsorship, particularly in the highly developed public engineering practice, has played a leading role. This includes the initiation and support of a large-scale research and development program on HPC, gathering together a large number of players in the civil engineering sector to form BHP 2000, and the preparation of an official design code for concretes with characteristic strengths up to 11,600 psi (80 MPa). Finally, HPC's improved properties of durability and rheology have always been exploited hand-in-hand with the mechanical properties. Hence the name "high performance concrete" as opposed to "high strength concrete."

Since 1983, over one hundred bridges have been built with HPC. They may be characterized by three approaches that correspond to the reasons for selecting HPC.

Structural Approach

The structural approach is based on enhanced mechanical properties. This leads to a reduction in materials and more slender structures. A parametric study performed by BHP 2000 has identified that span lengths could be increased by about 10 percent for equivalent design loads with the use of concretes with characteristic strengths of 11,600 psi (80 MPa) instead of 5800 psi (40 MPa). And so, new architectural concepts can become reality.

Among bridges that have been constructed and serve to illustrate this approach are the following:

- The cable-stayed bridges of Normandy, Le Pertuizet, L'Elorn, and recently Beaucaire-Tarascon, with a 656-ft (200-m) central span constructed with a ribbed slab 31 in. (800 mm) thick
- The cantilevered viaducts on the Southeast TGV line in Avignon and on the Lyon ring boulevard with a slenderness ratio of 25:1
- The arched bridges over the Rance and the Crozet Rivers near Grenoble with an opening of 459 ft (140 m) for the main arch, which is made up of two ribs 47 in. (1.20 m) wide with an average depth of 78 in. (2.0 m)
- The pylons of the Chavanon suspension bridge with a 984-ft (300-m) span

HPC was used on the Normandy Bridge to reduce member sizes

Construction Method Approach

The construction method approach is used to optimize construction cycles. This may involve high strength concrete at early ages to ensure rapid reuse of formwork and/or earlier prestressing. Placement of concrete in congested areas is also made easier by the rheology of HPC. Bridges based on this approach include the Ile de Ré bridge, which is 1.9 miles (3.0 km) long, includes 44,000 cu yd (34,000 cu m) of concrete, and was completed in 12 months. Le Corbusier viaduct in Lille and the bowstring bridge over the canal from the Marne to the Rhine rivers in Strasbourg are composite structures where HPC was used in prefabricated concrete slabs.

Maintenance Approach

The maintenance approach involves improved properties resulting from the highly closed microstructure of HPC leading to a lack of carbonation, slower diffusion of chlorides, and lower porosity. The maintenance approach is supported by the ongoing development of predictive computational models based on the actual characteristics of the materials and the environment surrounding the structure. Consequently, a contractual objective for a minimum service life is now possible using design rules and a material formulation model. French engineering firms were able to construct the Vasco da Gama Bridge in Lisbon with this performance and durability approach. The maintenance approach is of particular interest for small bridges,

*BHP 2000 Project is a national program to advance the use of HPC which are, by far, the most common and for which the potential benefits of reduced maintenance are greater.

Following construction of the experimental bridge at Joigny, the French Ministry of Development initiated the design of a range of standard bridges with the objective of improved durability. The first series has been constructed at Bourges, Angoulème, Sens, and Montpellier.

These bridges have a simple design consisting of a principal rib and very thin transversely ribbed cantilevers either prefabricated or cast-in-place. They make it possible to illustrate the three approaches described above:

- Structural—a 40 percent decrease in concrete volume, resulting in a very thin bridge deck and lighter foundations
- Construction Method—a gain of one week on a conventional construction cycle for the roadway
- Maintenance—better protection of the reinforcement from corrosion; thereby, generating substantial savings in maintenance and extending the service life

At present, the use of a wide range of HPCs is becoming more accepted. For example, the future bridge over the Rhine at Strasbourg is a prestressed concrete box girder with a central span of 673 ft (205 m) using concrete with a characteristic strength of 10,000 psi (70 MPa). Also, the use of prefabricated components and high early-age strengths for cast-in-place concrete or prefabricated components is increasing.

Considerable spin-offs have also been observed on all types of conventional concrete while the way has now been opened for the construction of the first experimental bridge with a 21,700 psi (150 MPa) fibrous concrete deck in Valence to be completed at the end of 2000.

Further Information

The following publications contain further information about High Performance Concrete in France:

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