APPLICATIONS OF HIGH PERFORMANCE LIGHTWEIGHT CONCRETE IN A FLOATING BARGE GATE

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Abstract

High Performance Lightweight Concrete (HPLC) has been extensively used in challenging marine environments. Its recent applications in a floating concrete barge gate with 100-year service life are presented together with the desired characteristics and corresponding mix designs. The additional protection system at construction joints to help the barge gate maintain long term serviceability is discussed in detail.

HPLC used in the barge gate has high-strength, high workability, low permeability, and high durability, which is essential to the structure's service life. Several key contributors to the HPLC's unique characteristics are identified. The use of lightweight high-strength porous shale as coarse aggregate in the HPLC is an important factor for both the light-weight and high-strength of the concrete. A low water/cementitious material ratio (w/cm) of 0.38 is another critical factor to enhance the durability of HPLC. Corrosion inhibitors such as DCIS can significantly enhance chloride tolerance for steel reinforcement, and were found to greatly extending the concrete structure's service life. The chloride corrosion analysis can provide guidance for the chloride invasion. Proper detailing of construction joints including the use of PVC waterstops and hydrophilic resins was also found to contribute to the durability of the concrete barge gate.

1 INTRODUCTION

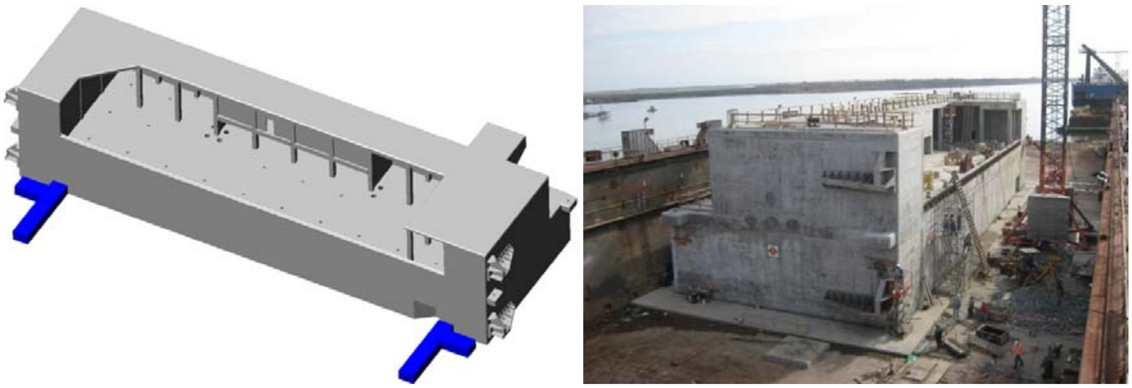
High Performance Lightweight Concrete (HPLC) generally refers to concrete that can achieve high performance such as high-strength, high workability, low permeability, and high durability while having low density. The unique characteristics of HPLC make it a preferable material used for many bridge projects. Researchers (Heffington *et al.*, 2001) have recommended the use of HPLC in prestressed concrete bridge girders and panels to save on transportation and construction cost. HPLC was also used in decks of Virginia Dare Bridge at Manteo of North Carolina, which was located in highly corrosive coastal environment.

In this paper, the application of HPLC in a floating concrete barge gate, together with its mix design and pertinent construction practices, to achieve the desired performance and 100-year service life is presented. The concrete barge gate (Figure 1) is designed for the Inner Harbor Navigation Canal (IHNC), Lake Borgne Hurricane Protection Barrier Project, in New Orleans, LA. It is 57.9 m long, 19.1 m wide and 13.3 m high, with a weight of 4873 ton and a draft of 4.4 m. When ballasted with water, the barge gate sets down on a foundation slab so as to close the navigable pass when hurricanes approach. After the hurricanes subside, the concrete barge gate is deballasted and floated back to its open position foundation to resume the traffic in the navigation channel.

The reasons for using HPLC are as follows. First, the concrete barge gate is frequently exposed to adverse environment factors including chloride corrosions, cyclic freezing and thawing, wave erosion, and barge impact. These factors not only impair the function of the barge gate but can also shorten its service lives. Once the concrete starts deteriorating, repair is possible, but can be costly, consequently, requirements for the durability of the barge gate are stringent. Compared to the 50-year life requirement for most of buildings, the concrete barge gate's service life requirement is 100 years. The achievement of such long service lives requires the imposition of strict requirements on factors related to the performance of the concrete including: permeability, durability and strength. Second, the floating concrete barge gate needs to have a light weight in order to meet operational requirements. Use of conventional concrete would significantly increase its self weight and draft depth, which reduces the clearance between the keel slab and its foundation slab therefore impairing the opening and closing operation.

Compared with Normal Strength Concrete (NSC), Structural Lightweight Concrete (SLC), and High Performance Concrete (HPC); HPLC have some unique characteristics. It combines many of the advantages of HPC and SLC. The unique characteristics in this case include high-strength, high workability, low permeability, light weight, and high durability. Although its cost is higher than NSC, the additional cost can usually be recovered from the reduced construction cost because of reduced dead weight.

The paper is organized in following manner. First, the desired characteristics of HPLC are presented. Next, the mix design to achieve the desired performance is discussed in detail. This is followed by a discussion of chloride corrosion analysis. Construction practices to achieve high durability are presented at the end.



(a) (b)

Figure 1 Concrete barge gate for the Inner Harbor Navigation Canal in New Orleans of LA (a) 3D model in Autocad (b) concrete barge gate under construction on a dry dock

2. CHARACTERISTICS

Laboratory tests (Figure 2) reveals that the strength of the HPLC used on the barge gate reached at least 27.6 MPa after 3 days (Figure 3). After 28 days, the strength was more than 48.1 MPa. The slump was 17.8 - 20.3 cm. After batching the HPLC had a good slump-life. The pozzolanic reaction between the lightweight aggregate and cement reduces microcracking in the interfacial zone. Permeability for HPLC is typically on the order of 1×10^{-10} cm/s, which is low compared to the permeability of low-strength concrete which is typically on the order of 30×10^{-10} cm/s (Mehta and Monteiro, 2006). The wet unit weight of the HPLC used on the barge was 1762-1842 kg/m^3, as compared to 2403 kg/m^3 for conventional concrete.

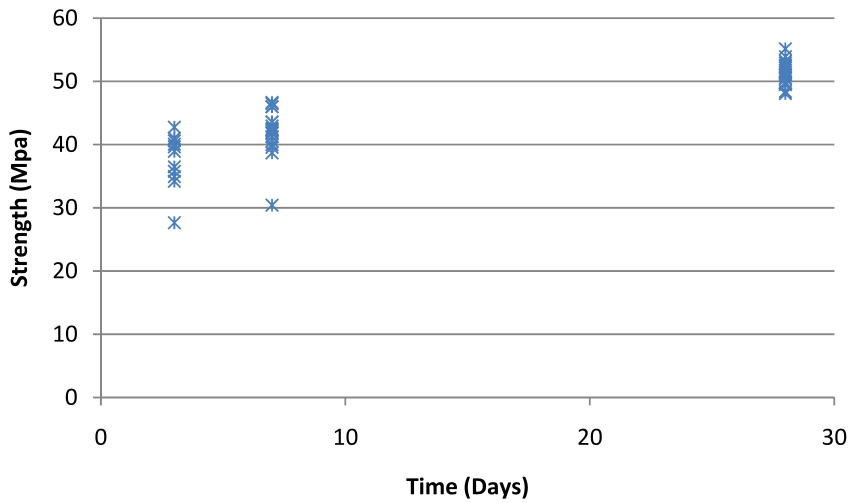


Figure 2 HPLC Strength Test Results with Time

3. CHLORIDE CORROSION ANALYSIS

Located in a brackish marsh, one of the most significant threats to the IHNC concrete barge gate's service life is chloride induced corrosion. The designed 100-year service life of the barge gate was verified by the concrete life cycle computer programs "Duramodel" and "ConcreteWorks" based on Fick's Second Law of Diffusion. Duramodel software introduced by Grace Construction Products can evaluate the performance and predict the service life of corrosion protection system based on data from specific projects (Timothy, 2000). Funded by Texas Department of Transportation, ConcreteWorks software was developed by the Concrete Durability Center at the University of Texas for the concrete mixture proportioning, thermal analysis, and chloride diffusion service life analysis (ConcreteWorks Version 2 Users Manual, 2005). One typical cross section of the concrete barge gate (12 inch concrete wall or slab with 2 inch cover) is selected for the analysis. Other inputs include the temperature, relative humidity, mix proportions, steel type, and chloride ion concentration etc. Both programs have predicted the concrete barge gate will last well over 100 year without a major repair.

The calculated chloride diffusion into the HPLC at 100 year after the complete construction by "ConcreteWorks" is shown in Figure 3. The maximum chloride ion concentration level in brackish water is assumed to be 0.0044 kg/m^3, which is at the exposed surface area. The extent of the chloride ion concentration at various depths of concrete gradually increases with time, which indicates a chloride intrusion. For the exposed side of a typical beam section with 5.1 cm concrete cover, the chloride ion concentration was calculated to be 0.21% after 100 years. This value is less than the steel rebar chloride ion corrosion threshold value (0.28%), which is mainly determined by the dosage (17.3 L/m^3) of calcium nitrite based corrosion inhibitors for black steel (ConcreteWorks Version 2 Users Manual, 2005). Therefore, after 100 years of service, even though the chloride ion was calculated to reach the steel reinforcing, the rebar should remain uncorroded.

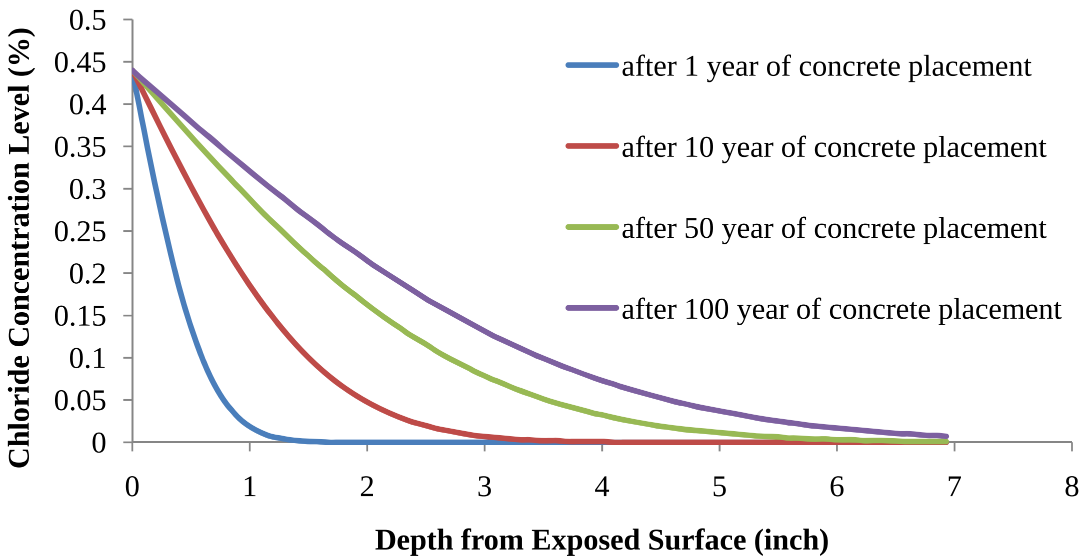


Figure 3 Chloride ion diffusion at various depths of concrete with time

4. MIX DESIGN

Selection of the components of the concrete mix design is a key to achieving high performance, and HPLC consists primarily of the same materials as conventional concrete. The mix proportions for the HPLC used in the barge gate are tabulated in Table 1.

Table 1 Proportion of mix for HPLC

Materials	Weight (kg/ m3)
Lightweight Coarse Aggregate	623
Fine Aggregate (Sand)	368
Cement	357
Lightweight Sand	178
Fly Ash	89
BASF MB90 (Air-Entraining Admixture)	321.1 mL
BASF Glenium 7101 (HRWR)	696.3 mL
DCIS (Corrosion Inhibitor)	17.3 L

w/cm ratio: 0.38
Air: 5-9%

The low unit weight of HPLC is mainly due to the use of lightweight aggregate (Figure 4), which has a density as low as 785 kg/m^3. A petrographic examination has been conducted for the lightweight coarse aggregate. The rock fragments are mainly composed of cloudy and nearly armorphous matrix material. The sieved sample consists of particles of particles retained on 9.5 mm, No.4, No.8, and No.16 standard sieves. The compressive strength is 33.5 MPa and splitting tensile strength is 2.7 MPa. The modulus of lightweight aggregate is found to be similar to the modulus of cement paste. Therefore, it reduces the stress concentration in the interface of aggregate and cement paste due to stiffness difference. The highly porous aggregate also contains moisture, which can be released to enhance curing and therefore reduce creep and shrinkage.

Research (Neville, 2003) has found that cement paste's strength can even exceed the strength of the coarse lightweight aggregate. With strong cement paste, the coarse aggregate can get crushed under high loading before the paste/aggregate interface breaks. Enhancing coarse aggregate strength can thus improve the hardened concrete strength. The coarse aggregate of the barge gate HPLC is made from high-quality shale (Figure 3). It has very high strength in excess of 82.7 MPa and low water absorption rate of approximately 6%.

For NSC the water/cementitious material ratio, w/cm, sometimes can be as high as 0.65. High w/cm ratios usually lead to the formation of relatively large micropores in the hardened cement paste. These relatively large micropores not only reduce concrete strength but also increase concrete's permeability because these interstitial voids provide a path for the invasive water, ions and chemicals. On the other hand, if the w/cm is less than 0.25, there is not enough water for the formation of ettringite, which also hampers the concrete strength. The workability of concrete becomes poor due to the lack of lubrication from insufficient cement paste. The optimal range of w/cm is within 0.25-0.4, which can be achieved with the application of High-Range Water-Reducing admixture (HRWR) or super-plasticizers. In this case, the HPLC has a low w/cm of 0.38 achieved by the use of HRWR.

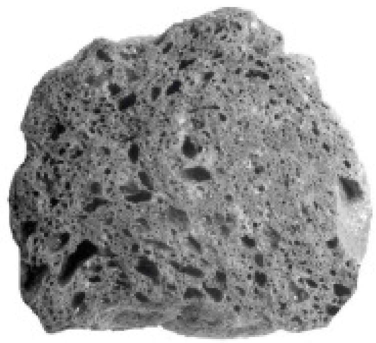
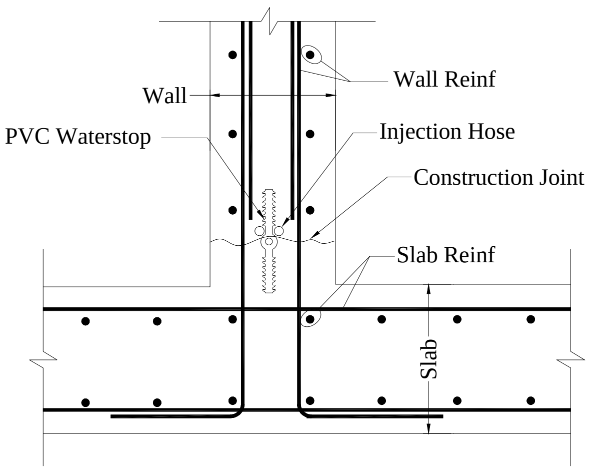


Figure 4 Cross section view of cellular highly porous lightweight aggregate (courtesy of Carolina Stalite Company)

Chemical admixtures play another important role in the mix proportioning of HPLC. Three types of admixtures have been applied in the barge gate mix: BASF MB90 (Air-Entraining Admixture), BASF Glenium 7101 (HRWR or super-plasticizers), and DCIS (Corrosion Inhibitor). Entrained air (typically 5%-9%) can reduce permeability and can also improve concrete plasticity and workability by reducing the segregation and bleeding during construction phase. The dosage of air-entraining admixture is determined on a trial-and-error basis. After measuring the air content in the trial, the dosage is adjusted to achieve the desired air content. Addition of HRWR has beneficial effects such as lower w/cm ratio at equivalent slumps and improved workability (ACI 212.4R-04). Dosage for HRWR is determined based on the recommendation range while considering the variations in concrete material, jobsite conditions, and application. The employment of corrosion inhibitor (DCIS) can significantly extend of marine structures' service life. The calcium nitrite in DCIS interacts with the embedded steel and forms an oxide layer to increase the tolerance of the steel to chloride in concrete. The typical dosage is 10 to 30 L/ m^3.

5. THE PROTECTION SYSTEM USED AT CONSTRUCTION JOINT OF THE BARGE GATE

Because of the size of the concrete barge gate, the occurrence of construction joint is inevitable. If not well protected, water will migrate through the joints and cause rebars to corrode. If corrosion products build-up around rebar surfaces, they take-up more volume than the parent steel; which can spall and crack the concrete around it. To minimize the impact of construction joints to the structure durability, a special protection system (Figure 5 (a)) was designed and implemented. In this system, a PVC waterstop was embedded in the center of construction joint. On both sides of the PVC waterstop there were two hoses for injecting hydrophilic resins (Fuko system). These hoses have staggered discharge openings and a one-way valve mechanism (Figure 5(b)). The lateral openings are covered by closed-pore neoprere strips against cement paste during concreting process. After the concrete above the construction joint was placed and hardened, the hydrophilic resin was pressure-injected through the pre-embedded hoses to infill any imperfections. The resins can also be re-injected for future maintenance purposes. The re-injected resin fills-in gaps between previous injections and the surrounding concrete to form an effective watertight barrier. A section cut after a re-injection is as shown in Figure 6. It can be seen that the injection and reinjection have fully filled voids in the honey combed concrete. The construction joint with this protection system can accommodate lateral and transverse joint movements while remaining watertight.



(a)

(b)

Figure 5 Protection system of PVC waterstop and hydrophilic injection hose (a) protection system (b) Re-injectable hydrophilic injection hose (Courtesy of Greenstreak Group, Inc)

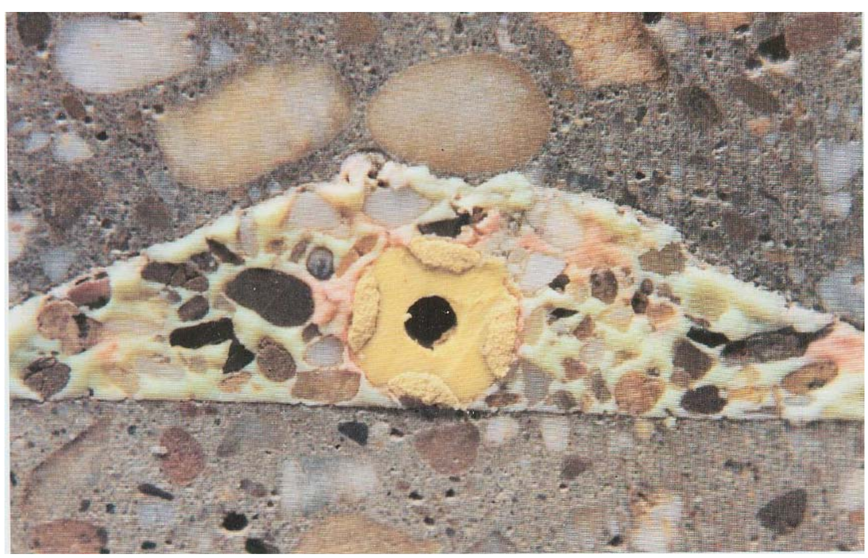


Figure 6 Reinjection of a honey-comb by duroseal inject (yellow: injection, red: reinjection) (Courtesy of Greenstreak Group, Inc)

6. CONCLUSION

HPLC used for a floating concrete barge gate have been introduced and discussed in details. HPLC is a very good candidate material because it can substantially reduce the dead weight while maintaining other high performance requirements. HPLC characteristics such as low permeability and high durability can significantly extend a structures' service life even in challenging environments, but close attention is required to the formulation of the mix design.

The highly porous lightweight aggregate contributes the most to the overall low unit weight and high strength of HPLC. Another contributor to high strength and high durability of HPLC is a low w/cm ratio of 0.38, which significantly reduces micropores in the hardened cement paste. The reduced workability due to low w/cm ratio can be compensated by the use of HRWR. Other chemical admixtures such as DCIS can substantially enhance the tolerance of the steel to chloride in concrete so as to extend the barge gate's service life in a highly corrosive environment.

Chloride corrosion analysis provides a clear prediction of the chloride invasion with time. At construction joint, the additional protection system by PVC waterstop and injecting hydrophilic resins can form a barrier to prevent water migration and associated rebar corrosion.

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