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High Performance Concrete in Florida Bridges

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Synopsis: A high performance concrete (HPC) mixture was developed in the laboratory and later used in a bridge construction project. The HPC mixture was designed based on 752 lbs (341 kg) of cement with 0.33 water to cement ratio. The weight of the cement was partially replaced by fly ash (20%) and silica fume (8%). The concrete mixture incorporated 4.5 gal/yd^3 (22.3 L/m^3) of calcium nitrite corrosion inhibiting admixture. Other chemical admixtures included air entraining agent, and/or standard and high range water reducing/retarding admixtures. A wide range of field and laboratory tests were performed on fabricated concrete specimens, as well as on cores from field models and newly cast bridge members. The main tests included field and laboratory testing of permeability, and compressive strength. Results of tests on laboratory and field concrete were very close. The chloride permeability (AASHTO T277) of the HPC was very low, ranging between 618 to 1055 coulombs. The compressive strength was high, ranging between 8600 to 10670 psi (59 to 74 MPa). This study shows that laboratory produced HPC with multiple cementitious materials and chemical admixtures can be successfully implemented in construction without compromising its durability. It is also demonstrated that sacrificial concrete models cast and cured at the job site can provide accurate evaluation of the durability and performance of newly cast structures. The study also emphasizes the need to test the permeability as well as strength for more precise assessment of concrete durability.

Keywords: Admixtures; bridges (structures); compressive strength; cores; durability; field tests; high performance concretes; mix proportioning; models; permeability; strength; tests.

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INTRODUCTION

There are over 3000 bridges along the 1200-mile coastline of Florida. They are exposed to extremely aggressive environment of the ocean water (1). With 17,000 ppm chloride content along the coastline, corrosion of the reinforcing steel in concrete is the primary concern in the substructure of these bridges. Corrosion of the steel is a result of poor quality concrete and insufficient concrete cover. In 1989, the annual cost of repairing corrosion related damage in Florida was estimated at 30 to 35 million dollars. In the Keys bridges alone, the repair costs have reached approximately 25% of the original cost of construction.

The challenge to engineers at the Florida Department of Transportation (FDOT) is to build durable bridges that can resist the adverse environment of ocean water. To meet this challenge, major emphasis is placed on building bridges with high quality concrete. The durability aspect is addressed in structural design, concrete-mixture selection and construction practices. Elements of design and construction that promote good durability and long term performance include adequate concrete cover and proper placement of reinforcing steel, and sufficient compaction and curing of the concrete.

Quality of the concrete mixture has a major impact on corrosion resistance of bridge structures. Concrete placed in severely aggressive environments should not only meet or exceed the specified strength, but also maintain high durability. Optimum strength and high durability are the two main characteristics of high-performance concrete (HPC) mixtures. HPC mixtures are designed with stronger emphasis on durability than in conventional concrete mixtures (2,3).

Permeability of concrete is considered a direct indicator of concrete durability. High permeability is the main contributor to poor durability and premature corrosion of bridge substructure. Based on this fact, research in Florida has strongly focused on concrete permeability. The research in Florida has set the following two objectives: to develop low-permeable HPC mixtures (4), and to develop laboratory and field test methods to measure permeability (5,6). The ultimate goal is to develop concrete durability specification and ratings based on permeability and strength requirements (7).

This paper addresses the development, specification requirement, research and utilization of HPC mixtures in Florida. A case study of a specific mixture is presented. The mixture has low water to cementitious materials ratio (W/CT). The cementitious materials consist of type II cement, silica fume (slurry form) and Class F fly ash. Chemical admixtures in the mixture include air entraining admixture, and/or ordinary water reducer/retarder, superplasticizer and calcium nitrite corrosion-inhibiting admixture. The concrete was tested for strength and permeability in the laboratory, and then used experimentally in a bridge widening project. Various tests were performed on field-produced concrete, including field and laboratory permeability tests, and compressive strength tests. A description of various permeability and strength tests is presented. The main laboratory and field test results are also discussed.

HPC SPECIFICATION IN FLORIDA

Research to develop HPC mixtures in Florida started in the mid 1970s. Compared to normal concrete, HPC mixtures have been designed with higher cement content and lower water to cement ratio. The HPC also include fly ash as a replacement of the cement to enhance concrete durability. The fly ash has been used in rates between 20 to 50 percent by weight of the cement.

The HPC mixtures were utilizes in the construction of the largest bridge project in Florida, the Sunshine Skyway Bridge (8). In the bridge substructure, fly ash was used to replace 50% of the cement in the concrete mixture. The use of high fly ash content was intended to satisfy two major objectives. First, to reduce concrete permeability for greater durability, and second, to reduce heat of hydration in the mass concrete elements to minimize thermal cracking.

Based on the experience from the Sunshine Skyway bridge and from results of numerous laboratory studies, a new concrete specification was derived for severely aggressive environments such as ocean water. The current FDOT specification requires the concrete mixture to have a maximum W/CT of 0.37, and a minimum total cementitious materials (including cement and pozzolans) content of 752 lb (341 kg) (9). For design purposes and calculation of ingredients (including those in this paper), the total cementitious content is initially assumed to be Portland cement. Fly ash is allowed to replace Between 20% to 50% of the weight of cement. Concrete mixtures with 50% fly ash replacement are used in mass concrete members. The minimum strength requirement for concrete at 28 days is 6500 psi (45 MPa).

The concrete specification also allows the replacement of between 50% to 70% of the cement with granulated blast furnace slag. The 50/50 slag/cement mixture is being used with good results in the construction of a major bridge in Jacksonville, Florida.

Despite greater emphasis on durability, the present FDOT specification contains no requirements for concrete permeability. Research efforts are underway to develop concrete durability specification and ratings based on both permeability and strength of concrete (7).

FLORIDA RESEARCH IN HPC

The emergence of silica fume and more advanced superplasticizers in 1980s brought about new opportunities for further improvements in the durability and strength of concrete. In 1989 the FDOT started a major research program in HPC (4). This followed a successful cooperative research effort between the FDOT and the University of Florida to develop field and laboratory tests for water permeability of concrete (5,6).

The FDOT research has three main objectives: To develop HPC mixtures with low permeability and moderately high compressive strengths (more than 6000 psi or 41 MPa); to implement the laboratory and field permeability tests in the evaluation of concrete durability; and to implement HPC mixtures and assure their durability in field. The ultimate goal is to develop durability specification and ratings for concrete based on permeability and strength.

Since the start of this research, a wide range of HPC mixtures have been produced and tested for strength and durability (4). These mixtures are designed with multiple cementitious materials, different water to cementitious materials ratio (W/CT) and a variety of chemical admixtures. Materials incorporated in the mixtures include, type I, II, and III cements, limestone and granite aggregates, Class F fly ash and silica fume, ASTM C494 Types D and F admixtures, and corrosion inhibiting admixtures. The testing program is designed to evaluate strength, elastic modulus, water and chloride permeability , corrosion and sulfate resistance of HPC.

In addition to laboratory testing of small concrete samples, six research models in the shape of 2.5 X 2.5 X 5.0 ft. (0.76 X 0.76 X 1.5 m) columns, have been cast outside the laboratory. The objective is to verify that mixtures proven under laboratory environment maintain their durability and strength properties in simulated field conditions. Two laboratory-proven concrete mixtures were prepared in a commercial mix plant. The concrete was transported by ready truck mixers and placed in the models. Cores were extracted from the models at various ages, and tested for strength and permeability in the laboratory. Field permeability tests were also performed on these models. Figure 1 shows the extensively cored research models. Results of the permeability and strength test on laboratory samples and research models are compiled in a large database file. From this database, criteria will be derived for the evaluation and classification of durability in concrete mixtures and structures. This will lead ultimately to the development of durability specification and rating system for concrete.

CORROSION-INHIBITING HPC IN BRIDGE CONSTRUCTION

A decision by the FDOT to stop the use of epoxy-coated reinforcing bars in new bridges prompted an urgent need to develop alternatives with effective corrosion protection systems. The ongoing research in Florida has shown that concrete mixtures with type II cement, 20% Class F fly ash, 5 to 10 percent silica fume (slurry form), superplasticizers and a maximum W/CT of 0.35 produce concrete with low permeability, high strength and excellent corrosion resistance (4). These HPC mixtures were considered as obvious alternates to the epoxy-coating of the reinforcing bars. In addition, calcium nitrite corrosion inhibiting admixture was also selected for the HPC mixtures to further enhance the corrosion protection of the reinforcing steel.

However, there was little information on the use and performance of concrete with corrosion inhibitors in Florida. Therefore it was necessary to develop performance data from laboratory and field evaluation of this concrete. A plan was developed by which the HPC mixture would first be evaluated in the laboratory, and a preliminary materials specification would then be developed. The mixture would then be utilized and its properties verified in the field. Once this task has been accomplished the specification would then be finalized for application in bridge construction projects.

Scope of Testing Program

Table 1 shows the designs and plastic properties of all laboratory and filed mixture. Two concrete mixtures were designed, batched and tested in the laboratory. The first mixture included fly ash and 5.5 gal/yd^3 (27.3 L/m^3) of calcium nitrite. The second included fly ash, silica fume and 4.5 gal/yd^3 (22.3 L/m^3) calcium nitrite. Field mixtures were designed with similar ingredients as in laboratory mix 2. Field mixtures were batched in concrete and prestress plants. The jobsite mixture was almost identical to the concrete plant mix.

An extensive testing program was developed to evaluate properties of the laboratory and field produced concrete. Laboratory specimens and field models were fabricated and tested to evaluate properties of the concrete. A wide range of laboratory tests were performed, including compressive strength, rapid chloride permeability (AASHTO T277), and laboratory water-permeability.

Large scale models were cast at the concrete plant, jobsite and prestress yard. A full-scale 15-foot (4.6 m) pile cap was cast at the concrete plant to evaluate general properties and handling of concrete in a large member. At the jobsite, a 2.5 X 2.5 X 4.0 ft (0.76 X 0.76 X 1.22 m) model of a column was cast from the same concrete that was used in casting the actual structural members. A one foot (300 mm) cube test-block was also prepared at the prestress plant. Cores were obtained from the model at the concrete plant and jobsite, as well as from the actual structural members. The cores were subsequently tested for strength and laboratory permeability. In addition, field permeability tests were performed on all three models and on some structural members.

Courtney Campbell Bridge

The corrosion inhibiting HPC mixture was implemented in the field on an experimental bases. The mixture was used to cast piles and pile caps to widen a small bridge on the Courtney Campbell Causeway in Clearwater, Florida. This was the first field application of a concrete mixture containing silica fume, fly ash and corrosion inhibitor in Florida. The bridge is 473 ft. (144 m) long with eleven 43-foot (13 m) spans. It allowed traffic in both directions. In this project, each side of the bridge was to be widened by approximately 18 feet (5.5 m). The additional width, will provide two 10-foot (3 m) outside shoulders, two 8-foot (2.4 m) inside shoulders and two 12-foot (3.7 m) lanes in each direction. Figure 2 shows a view of the construction site.

Project specifications called for the use of corrosion inhibiting HPC mixture in the substructure. The concrete was used in all piles, pile caps and end walls. The piles were 18-inch (0.46 m) square prestressed members with 3 in (75 mm) concrete cover. Each pile cap was extended an additional 15 feet (4.6 m), and was supported by two piles. The pile caps were cast-in-place. A total of 2550 linear feet (777 m) of prestress piles were cast. The total amount of HPC placed in the pile caps and end walls was 121 yd^3 (92.5 m^3).

Laboratory Mixtures

Two laboratory trial mixtures were batched and tested. Table 1 shows mixture designs and plastic properties for the two mixtures. The total cementitious material content for each mix was 752 lb (341 kg). Mix 1 contained 20% of Class F fly ash and 5.5 gal/yd^3 (27.3) of calcium nitrite, with no silica fume. Mix 2 had 8% silica fume (slurry form), 20% fly ash and 4.5 gal/yd^3 (22.3 L/m^3) of calcium nitrite. Type II cement was used in both mixtures. Tables 2 and 3 show the chemical and physical properties of cement and Class F fly ash. The aggregates consisted of Florida crushed limestone aggregates (grade 67) and silica sand. The ordinary water reducer (LRWR) and the high range water reducer (HRWR) were ASTM C494 Types D and F, respectively. The calcium nitrite was the non-accelerating type (contained a set retarder) formulated to prevent premature stiffening of the mixtures.

Both mixtures had good workability as indicated by high slump. In mix 2, the air content was lower and the unit weight was higher than in mix 1. This is may be attributed to the silica fume which has the tendency to reduce the air content and increase the density of concrete. The concrete specimens were cast in plastic molds. After 24 hours, the specimens were demolded and placed in lime water for curing until test date.

<u>Field Mixtures</u>

Three mixture designs were implemented in the field, as shown in Table 1. The concrete-plant mixture was batched in the plant to verify the mixture design for acceptance purposes. In this mixture, grade 57 aggregate (1 in. or 25 mm maximum aggregate size) was used. The concrete was used to cast the pile-cap model at the plant.

The prestress plant mixture was used to cast all the piles for the widening project, as well as the one-foot cube test block. Only air and HRWR were used in the prestress plant mixture.

The jobsite mixture is a modification of the concrete plant mixture. The difference is that the jobsite mixture was designed with grade 67 aggregate (3/4 in. or 20 mm maximum aggregate size). The jobsite concrete was used to cast the pile caps and end walls of the bridge, and the column-model at the jobsite.

The three field mixtures are almost identical to laboratory mix 2, except for two distinct differences. Field mixtures used 69 oz. (2 L) of ASTM C 494 Type G HRWR which is also a set retarder, as compared to 5 oz. (0.15 L) of ASTM Type F regular set HRWR in laboratory Mix 2. The second difference is that the field mixtures included air entraining agent. The modifications in type and dosages of admixtures were necessary to offset any early stiffening of the concrete form the use of calcium nitrite, and also to maintain the target slump for at least 90 minutes after mixing.

<u>Construction</u>

The work at the concrete plant, prestress plant and jobsite was closely monitored. There were no problems with workability or early stiffening of the concrete. Even at the jobsite, when the truck mixers were discharging concrete in a timely manner, no workability problems were encountered. However, the concrete slump did drop from 4.5 to 2.5 inches (114 to 64) during a 60 minute period while a truck was waiting to discharge.

The pile caps and wing walls were cast-in-place. Wood forms were used for casting. The piles were fabricated in metal forms in a prestress plant. During concrete placement, fine mist was sprayed above the cast area. After placement, the finished concrete surface was wet cured under a curing blanket/burlap for 7 days. After 7 days, curing compound was applied to the finished surface. No cracking was observed on the prestress piles or on the cast-in-place pile caps/wing walls.

The concrete specimens in the field were cast in plastic molds, covered, and were left at the jobsite for 24 hours. Then they were transported to the laboratory to be cured in lime water until test time. The column-model at the jobsite was cast in a metal form unlike the wood forms of the pile caps and wing walls. The form was removed after 48 hours. The model was then wrapped with burlap and kept wet for 7 days. The pile-cap model was cast at the concrete plant using a wood form. The casting and curing were similar to those used at the jobsite. The concrete block at the prestress plant was cast in a wood form, and was cured similar to the prestress piles.

Compressive Strength

Table 4 shows the compressive strength of concrete at ages 1, 3, 7, 14, 28, and 91. At each age, three 6 X 12-inch (150 X 300 mm) samples were tested. Each value in Table 4 represents the average of three test results. The rate of strength development for lab mix 2 was significantly higher than mix 1. Silica fume contributed to the increase in the strength of concrete. The increase in compressive strength ranged between 14% at 7 days to 24% at 28 days.

All field mixtures had lower compressive strength than lab mix 2. The reduction of strength at 28 days for concrete plant mixture, prestress mixture, and jobsite mixture was 20%, 6%, and 4%, respectively. However the compressive strengths of these mixtures were still above the 6500 psi requirement for concrete acceptance. Furthermore, strengths of concrete at the jobsite and prestress plant were very close to the strength of laboratory concrete. This shows that using HPC mixtures in the field will not result in significant decrease in the compressive strength. The key factor in duplicating laboratory properties of HPC in the field is to maintain a high quality control during production of concrete.

Laboratory Permeability Tests

Two permeability tests were performed on the laboratory and field mixtures. The tests were the Rapid

Chloride Permeability Test (RCPT), and the Laboratory Water-Permeability Test (LWPT). The RCPT was performed according to AASHTO T277 and ASTM C1202-91. Figure 3 shows the test apparatus for the rapid chloride permeability test.

The LWPT is a water permeability test procedure developed in Florida. Reference 5 presents detailed information on the test. Figure 4 shows the test system. The test specimen is a 2 in. (50 mm) thick slice of concrete cut from a 4 in. (100 mm) diameter cylinder or core. The specimen is coated on its perimeter with 1 in. (25 mm) thick epoxy. It is then securely sealed in the permeameter cell and connected to a manometer tube, as shown in Figure 4.

The test begins by injecting water into the manometer tube and reservoir of the permeameter cell. This is followed by applying 100 psi (0.69 MPa) pressure inside the system to force the water into the concrete specimen. The amount of water flowing into the specimen is monitored on the manometer tube until a steady-state flow is reached. Experience has shown that the steady-state flow is reached after 14 to 21 days. The test is continued for additional 7 days, during which the flow of water is recorded at 24-hour intervals.

To obtain the coefficient of permeability, the cumulative amount of water is plotted versus elapsed time. Then, using statistical methods, the best fit linear-curve is established for the data points. This is followed by determining the slope of the curve. Finally, Darcy's formula is used to determine the water permeability of concrete. The test is normally completed between 28 and 31 days. Efforts are underway to reduce testing time in order to obtain the results in a shorter period of time.

All test samples were cured in water until time of testing. Table 5 shows the averages of results of water and chloride permeability tests. The tests were performed twice during the first 91 days. Each time, Two specimens were tested. In some cases, additional specimens were tested at ages beyond 91 days. The water/chloride permeability did not necessarily decrease after 28 days. In some cases, the results showed a slight increase in permeability. The variation in test results is not unusual for two main reasons. First, it can be hypothesized that HPC mixtures may develop very low levels of permeability at 28 days, and more or less maintains that plateau beyond this age. Second, according to ASTM C1202-91, a variation as high as 35% is expected in the chloride permeability test results. It