

High Performance Concrete for Bridge I-Girders

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High Performance Concrete (HPC) is a new type of concrete made with selected high quality constituents, optimized mix design, and low water-to-powder ratio. According to the American Concrete Institute (ACI), HPC is defined as concrete meeting special combination of characteristics and uniformity requirements. HPC cannot always be achieved using conventional mix constituents or regular mixing and quality control procedures.
The objective of this research is to develop economic, self-consolidating high performance concrete mixes to be used in the precast industry of bridge I-girders. The produced mix attains a minimum 28-day strength of 15 ksi., mixing time below 20 minutes to avoid the formation of cold joints upon girders' fabrication, and self-consolidating workability (spread diameter of 23 inches or more). Designed mixes were used to fabricate prestressed girders. Steps of mix design are mentioned. Developed HPC were used in fabricating high strength girders for full-scale testing. The girder test results proved the superior performance of the developed HPC mixes in shear and flexure. HPC mixes are economic to use in fabricating I-girders due to their higher strength and expected long-term durability.

Key Words: High performance concrete; HPC, Proprietary mixes, Self-consolidating concrete; SCC

Introduction

The term High Performance Concrete (HPC) is used to describe concrete mixes made with selected high quality constituents, optimized mix design, and low water-to-powder ratio. According to the American Concrete Institute (ACI), HPC is defined as concrete meeting special combination of characteristics and uniformity requirements, which cannot be achieved using conventional constituents, regular mixing and curing procedures. The characteristics and requirements considered for HPC definition are:

1. Ease of placement (good filling and passing ability).
2. High early strength.
3. Long-term mechanical properties.
4. Permeability.
5. Volume stability.
6. Long life in severe environments (durability).

In 1987, the Congress initiated a five-year Strategic Highway Research program (SHRP) to investigate different concrete products to improve the standards of the nation's highways and bridges, and reduce the maintenance and rehabilitation activities. In order to set a definition for HPC, a SHRP study (Zia et al, 1991) specified the following criteria for HPC definition:

1. A maximum water-to-powder ratio of 0.35.
2. A minimum durability factor of 80%, as determined by ASTM C666.
3. Strength criteria of: 3000 psi at age of 4 hours, 5000 psi at age of 24 hours, and10000 psi at age of 28 days.

In 1993, the Federal Highway Administration (FHWA) initiated a national program to introduce HPC to the bridge construction industry. The FHWA program included the construction of HPC demonstration bridges in all FHWA regions. The technology and results of HPC bridge construction were presented at showcase workshops. The intent of this program was to show the different States how they can benefit from the use of HPC in bridge construction. According to the FHWA, HPC is defined as "A concrete: made with appropriate materials combined according to a selected mix design; properly mixed, transported, placed, consolidated and cured so that the resulting concrete will

give excellent performance in the structure in which it is placed, in the environment to which it is exposed and with the loads to which it will be subject for its design life".
HPC mix development depends mainly on the selection and proportioning of mix constituents. HPC constituent materials are proportioned to achieve an optimized packing order for the granular mixture. The optimized particle gradation results in a low void ratio and higher strength. The largest granular material in the HPC mix is fine sand, with a particle size ranging from 150 µm. to 600 µm. Cement particles have the second largest size in the mix, with a nominal size of 15 µm. Quartz flour has nominal diameter of 10 µm. Silica fume is the finest particle in the mix, with a nominal size of 1 µm. Silica fume size is sufficient to fill the voids among other mix constituents.

Supplementary cementitious materials as silica fume and quartz flour are used in HPC mixes to increase the concrete performance characteristics. Silica fume, as a very reactive pozzolanic, reacts with the calcium hydroxide resulting from Portland cement hydration. This reaction forms additional binder material called calcium silicate hydrate. This additional binder improves the HPC hardened properties. In addition, silica fume increases the cohesion of fresh concrete, which reduces segregation and bleeding. The extreme fine size of silica fume particles minimizes the voids in hardened concrete. This results in reduced permeability and enhanced mechanical properties. Quartz flour is used as a supplementary cementitious material, with a particle size larger than silica fume and smaller than cement, to improve the mix particle gradation. Due to the low water-to-powder ratio (powder includes cement, silica fume, and fly ash) of HPC mixes, a significant portion of Portland cement particles remains un-hydrated. The un-hydrated cement particles remain inert within the mix, and act like fine aggregate particles. In a relevant study, Ma and Schneider (2002) gradually replaced portions of the cement with quartz flour of equivalent volume. The replacement of cement portions up to 30% (by weight) did not affect the final strength of the mix.

Development of Non-Proprietary HPC Mixes at the University of Nebraska

In year 2006, researchers at the University of Nebraska – Lincoln attempted to produce non-proprietary HPC mixes using a high energy food processing mixer. The Hobart food mixer, shown in **Fig. 1**, was used as regular drum mixers were incapable of providing enough energy to produce HPC mixes with low water-to-powder ratio. Type I/II cement was used and water-to-powder ratios ranging from 0.13 to 0.16 were tried. A final compressive strength of 17 ksi was achieved. Developed mixes had a material cost of $380 per cubic yard (Kleymann et al., 2006).

Figure 1: Hobart food mixer

In this current research, a high energy vertical-shaft mortar mixer was used. The mixer, shown in **Fig. 2**, has a 5.5 horse power motor, a drum capacity of 27 ft^3, and a batch output of 17 ft^3. The non-proprietary HPC mix was designed to achieve the research purposes. First, class C fly ash was used to replace quartz flour. The use of fly ash as a waste product in producing concrete has a positive economical and environmental impact. Second, type III Portland cement was used in mix production. The use of Type III cement was required to achieve early high strength.

Figure 2: Vertical-shaft mortar mixer

Micro silica was used to increase the mix initial and final strength. The use of micro silica and class C fly ash as supplementary cementitious material, in addition to maintaining a low water-to-powder ratio was sufficient to develop the required strength. The material cost of the developed mix was calculated based on the cost of constituents at the local market, which include \$95 per ton for type III Portland cement, \$15 per ton for class C fly ash, \$600 per ton for micro silica, \$15 per ton for ¼ in. limestone, \$10 per ton for fine sand, and \$10 per gallon for the HRWR. The design and material cost of developed mixes are shown in **Table 1**.

Table 1

Design and material cost of developed mixes

Constituent/yd^3	**Mix # 1**	**Mix #2**	**Mix #3**	**Mix #4**	**Mix #5**
Cement, lbs	1050	1040	1050	1120	1050
C fly ash, lbs	300	130	300	240	300
Silica fume, lbs	150	130	150	240	150
#10 Sand, lbs	2255	2428	1580	2255	1580
Limestone, lbs	0	0	672	0	672
Water, lbs	225	260	240	240	235
HRWR, lbs	62	35	62	71	72
Cost, \$/yd^3	**\$205**	**\$140**	**\$180**	**\$220**	**\$190**

Application of Non-Proprietary Mixes in Precast/Prestressed Bridge I-Girders

The high strength of the afore-mentioned mixes (15 ksi, 15.5 ksi, 17 ksi, 14.8 ksi, and 14.7 ksi respectively) and their low cost of the developed non-proprietary HPC mixes allowed for the fabrication and testing of different types of precast/prestressed I-girders. Girders were fabricated at Coreslab Omaha, Inc. and tested at the structural testing center of the University of Nebraska – Lincoln. Examples of full-scale testing application are:

First I-Girder Fabricated with 0.7 inch. Strands at 2.0 inch Spacing in North America

The first girder fabricated with 0.7 in. prestressing strands at a vertical and horizontal spacing of 2.0 in was tested at the University of Nebraska - Lincoln. The girder had a NU900 cross section, and contained 30-0.7 inch strands at its bottom flange. A one in. haunch and 7.5 inch slab were poured on top of the top flange. When tested to its ultimate capacity using a point load acting on a 15 ft., as shown in **Fig. 3**, a load of 800 kips (which exceeds the girder capacity) was applied to the girder top flange that caused visual shear and flexure cracks. However, no strand slippage was observed. The high strength of the girder concrete, in addition to strands confinement, had a major role in preventing strands slippage; cracks appearing on the tested girder are shown in **Fig. 4**. For additional details, refer to Akhnoukh (2009)

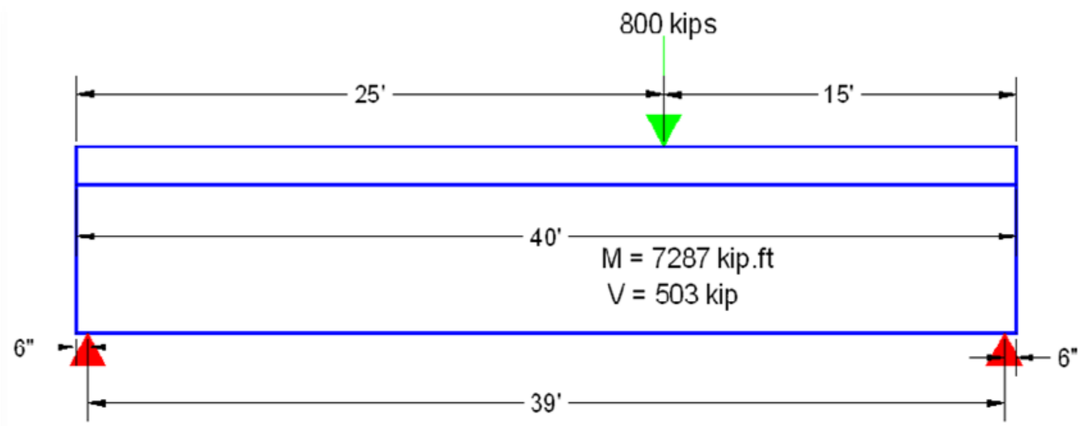

Figure 3: NU900 girder test set-up

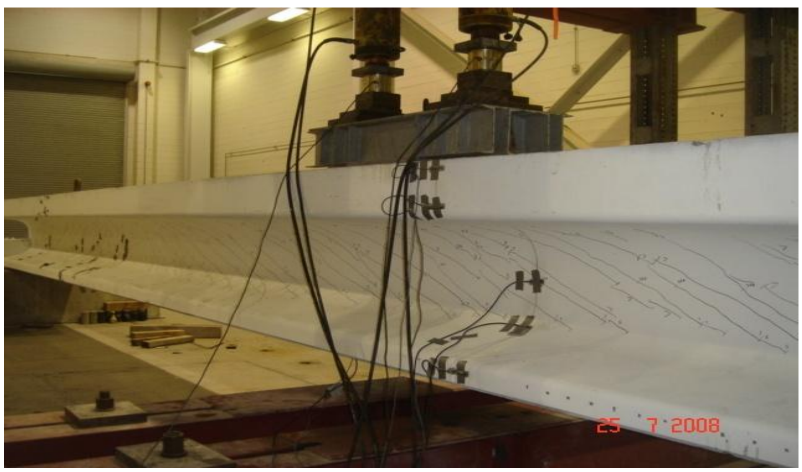

Figure 4: NU900 Girder Cracks

The Use of Welded Wire Reinforcement (WWR) as Shear Reinforcement of Precast/Prestressed HPC I-Girders

The performance of WWR as shear reinforcement of precast/prestressed I-girders was investigated. Two AASHTO Type II I-girders were fabricated using HPC mix #4 (refer to table 1) and tested in shear until failure was achieved. WWR was used in girder fabrication to replace the random steel fibers incorporated in the HPC proprietary mixes. Due to heavy girder reinforcement, shown in **Fig. 5**, the concrete flowing ability was tested instantly prior to pouring. The final concrete spread was 29 inch as shown in **Fig. 6**.

Figure 5: WWR used in AASHTO type II girder fabrication

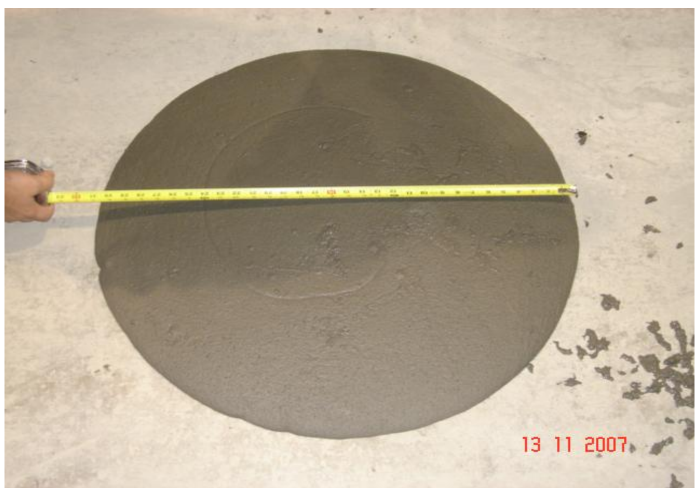

Figure 6: Slump flow test for HSC concrete used in pouring I-girders

The 2 girders were tested in shear through similar test setup as shown in **Fig 7**. Testing result of AASHTO girders proved the superior performance of developed HPC mixes and WWR. The final shear capacity of the two girders were 497 and 433 kips.

Figure 7: AASHTO Type II girders test set-up

The shear failure of the tested girders was achieved with extensive shear cracks at the girder shear span, and failure of end diaphragm. The average shear capacity of the two tested girders was significantly higher than capacity of similar sections fabricated with normal concrete and conventional shear reinforcement. In addition, the WWR performance was highly predicted by the current AASHTO LRFD specifications. In addition, the use of self-consolidating HPC mix and WWR meshes resulted in ease of construction. The failure pattern for the tested girders is shown in **Fig. 8** and **Fig. 9.**

Figure 8: Shear cracks at failure of AASHTO Type II girders

Figure 9: Diaphragm failure at shear ultimate loading

Summary and Conclusions

Economical non-proprietary HPC mixes were developed to be used in the construction industry in the US local market. Developed mixes had superior strength and flowing ability compared to normal concrete mixes. The performance of the developed HPC mixes was tested in precast/prestressed bridge I-girder applications. The superior properties of the developed mixes and high flowing ability resulted in significant increase in shear and flexure capacities of tested girders. In addition, larger prestressing strands with 0.7 inch diameters were successfully used at a vertical and horizontal spacing of 2.0 in. without slippages. These research findings may result in a wider spread of non-proprietary HPC mixes in the precast/prestressed industry in general; and in girder bridge construction in particular.

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