Reactive Powder Concrete Application in the Construction Industry in the United States

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Abstract

Reactive powder concrete (RPC) is a new class of concrete developed in France in the 1990s. RPC mixes shows superior material properties as high early strength, higher compressive and tensile strength, durability and higher resistance to shrinkage, creep, and hard environmental conditions. Currently, RPC is introduced to the US market through the FHWA and is commercially known as *ultra-high-performance concrete* (UHPC).

UHPC displayed superior performance in high-rise building construction and prestressed concrete girder bridges. The high early strength results in expedited fabrication at precast yards. The RPC high strength results in smaller cross sections, lighter weight structures, reduced labor, and construction equipment with smaller capacities. In 2010, the FHWA started using RPC in various bridge construction and repair projects using the accelerated bridge construction (ABC) innovative approach. This paper presents the history of RPC, RPC mix constituents, advantages, and its application in prefabricated bridge elements and systems construction (PBES).

Keywords
Reactive Powder Concrete (RPC), Ultra-High Performance Concrete (UHPC), Pi-girder, Compressive Strength

1. Introduction

Reactive powder concrete (RPC) is a new class of concrete that has been developed in France in the 1990's. When compared with other types of concrete, RPC shows superior material properties as high early strength, higher tensile and compressive strength, durability, and higher resistance to shrinkage, creep, and hard environmental conditions. In early 2000s, the Federal Highway Administration (FHWA) and State

Departments of Transportation (DoTs) introduced the RPC mixes to the US construction industry with emphasis on long-span prefabricated bridge girders. RPC is commercially available in the US market under the name ultra-high-performance concrete (UHPC).

Standards and specifications for RPC are set by different scientific societies in Europe and Japan. The Japan Society of Civil Engineers (JSCE) *Recommendation for Design and Construction of Ultra-High Strength Fiber Reinforced Concrete (draft)* (JSCE, 2006) defines the UHPC as a type of cementitious composite reinforced by fibers with characteristic values in excess of 150 N/mm2 (21.7 ksi) in compressive strength, 5 N/mm2 (0.73 ksi) in tensile strength, and 4 N/mm2 (0.58 ksi) in first cracking strength. The UHPC matrix should be composed of aggregates; whose maximum particle size is less than 2.5 mm, cement and pozzolans, and water-to-powder ratio is less than 0.24. UHPC contains random reinforcing steel fibers of more than 2% (by volume), whose tensile strength exceeds 2 x 103 N/mm2 (290 ksi), and ranges from 10 to 20 mm in length and 0.1 to 0.25 mm in diameter. The Association Francaise de Genie Civil (AFGC) *Interim Recommendations for Ultra-High-Performance Fiber-Reinforced Concrete (2002)* defines the UHPC as a material with a cement matrix and a characteristic compressive strength in excess of 150 MPa (21.7 ksi), and containing streel fibers in order to achieve ductile behavior. According to the AFGC, the following are the main difference between the UHPC and other types of concrete:

- Higher compressive strength
- Incorporation of random steel fibers in the mix, which ensures the non-brittle mix behavior, and alters the conventional reinforcement of passive reinforcement
- High binder content and special selection of aggregates

Different UHPC proprietary mixes are available in the international markets with standard characteristics. Example of the proprietary mixes are BSI "Beton Special Industrial" (Special Industrial Concrete) developed by Eiffage, Cemtec by LCPC, and different kinds of Ductal concrete resulting from a joint research by Bouygues, LaFarge, and Rhodia. Ductal concrete marketed by LaFarge and Bouygues is the only proprietary RPC (UHPC) mix available in the US market. This paper presents main mix constituents for the proprietary RPC mix available in the US market, its advantages, and the main impediments that delays the widespread of RPC in construction projects in the local and international markets.

2. Reactive Powder Concrete Main Constituents

The RPC mix constituents are proportioned to achieve an optimized packing order by reducing the voids ratio of the granular constituents of the RPC. The granular mix constituents include fine sand, cement, quartz flour, and micro-silica (silica fume). The largest granular material available is fine sand, with a particle size ranging from 150 to 600 µm. Cement particles have the second largest size in the mix, with a nominal size of 10 µm. Micro-silica is the smallest particle with the RPC mix, with a diameter of 1 µm. The micro-sized silica particles have a small diameter sufficient to fill the voids among the mix constituents, hence, it increases the packing order and positively impact the strength and long-term performance of the RPC.

Random steel fibers are added to the proprietary RPC mix to ensure its ductile behavior and increase the tensile strength of the mix. Fibers are the largest mix constituent, with a nominal diameter of 0.008 in. and a length of 0.5 in. Its average modulus of elasticity (E) is 29,800 ksi, and the average ultimate strength is 474 ksi. Steel fibers are separately added to the mix ingredients, and represent 2% of the final volume of the mix, and 6% of its weight. Steel fibers are a major contributor to the concrete high compressive strength, in addition to its major role in the RPC mix ductility, and enhanced long-term performance as low shrinkage and low creep. The design of the standard RPC mix marketed in the local construction market within the United States by LaFarge-under the commercial name Ductal is shown in the Table (1)

Table 1: UHPC Mix Composition (Publication No. FHWA-HRT-06-103)

Material	Amount (lb/yd^3)	Percent by Weight
Portland Cement	1200	28.5
Fine Sand	1720	40.8
Micro-Silica	390	9.3
Quartz Flour	355	8.4
Super-plasticizer	51.8	1.2
Accelerator	50.5	1.2
Steel Fibers	263	6.2

3. Reactive Powder Concrete Mix Properties

The mix composition of the RPC includes a high binder content (approximately 1950 lbs per cubic yard) as compared to 500 lbs per cubic yard in a regular mix results in a higher compressive strength. The presence of steel fibers contributes to the increased compressive strength and results in a higher ductility for the RPC. In a recent study, proprietary RPC mixes had a 28-day compressive strength of 25 ksi, and non-proprietary mixes excluding the steel fibers had a compressive strength of 18 ksi at the same age (Akhnoukh and Xie, 2010). RPC mixes are characterized by a higher density due to its higher packing order, and reduced voids ratio. Standard proprietary mix designs have an average density of 150 to 155 pcf, as compared to densities of 142-145 pcf for conventional concrete mixes.

Recent research studies have investigated the optimum mixing regimen to produce RPC mixes with superior mechanical properties and long-term performance characteristics. Based on research findings, the following steps are considered when mixing RPC:

1. Preblended granular material are added to the batch plant mixer for dry mixing for a total duration of 2-3 minutes
2. One-half of the super-plasticizer amount is added to the total weight of mixing water. Mixing water should be of a very low temperature (close to freezing point). Super-plasticizer and cold water are blended together outside the concrete-mixer
3. Mixing water and superplasticizer are slowly added to the concrete mixer containing the dry mixed granular material. Wet mixing continues for 15-20 minutes
4. The remaining amount of super-plasticizer is added to the mixer. Mixing continues for 5 minutes
5. Random steel fibers are added to the mixer. Fibers are slowly added to ensure the even distribution of steel fibers within the produced RPC mix.

The afore-mentioned mixing procedure spans for a total period of 30 minutes, which is adequate to produce a mix with optimum rheology without impeding the work progress in batch plants. RPC produced using this mixing regimen attain the following characteristics:

- **Compressive Strength:** exceeds 2.7 ksi as per standard specifications. Research studies reported an average 24-hour compressive strength of 12-14 ksi, and a 28-day compressive strength of 24
- **Post-Cracking Strength:** of 1.6-1.8 ksi due to the ductile behavior achieved using random steel fibers within the mix.
- **Modulus of Elasticity:** at release is 5000 psi and is approximately 7500 psi at 28 days. This high value of modulus of elasticity is beneficial in reducing deflection and meeting serviceability requirements of high-way bridge girders.
- **Corrosion Resistance:** are increased in RPC concrete due to the higher packing order of the granular materials, which reduces the voids ratio and minimizes the chloride attack to the reinforcing steel and prestress strands embedded in the RPC structural members
- **Freeze and Thaw Resistance:** RPC mixes are characterized by superior freeze and thaw cycles resistance due to the high packing order of its granular materials, and the lack of air voids within the concrete. The lack of voids results in the absence of free space for water to freeze and increase in volume.

The superior characteristics of the RPC beams fabricated using proprietary mixes as Ductal allows for the design of bridge girders with very high span-to-depth ratios. Span-to-depth ratio of 30:1 was achieved in multiple bridge projects, resulting in lighter weight and more durable bridges. A comparison of depths of different I-girders with similar capacities produced by regular RC mixes, RPC mixes, and steel are shown in Figure 1.

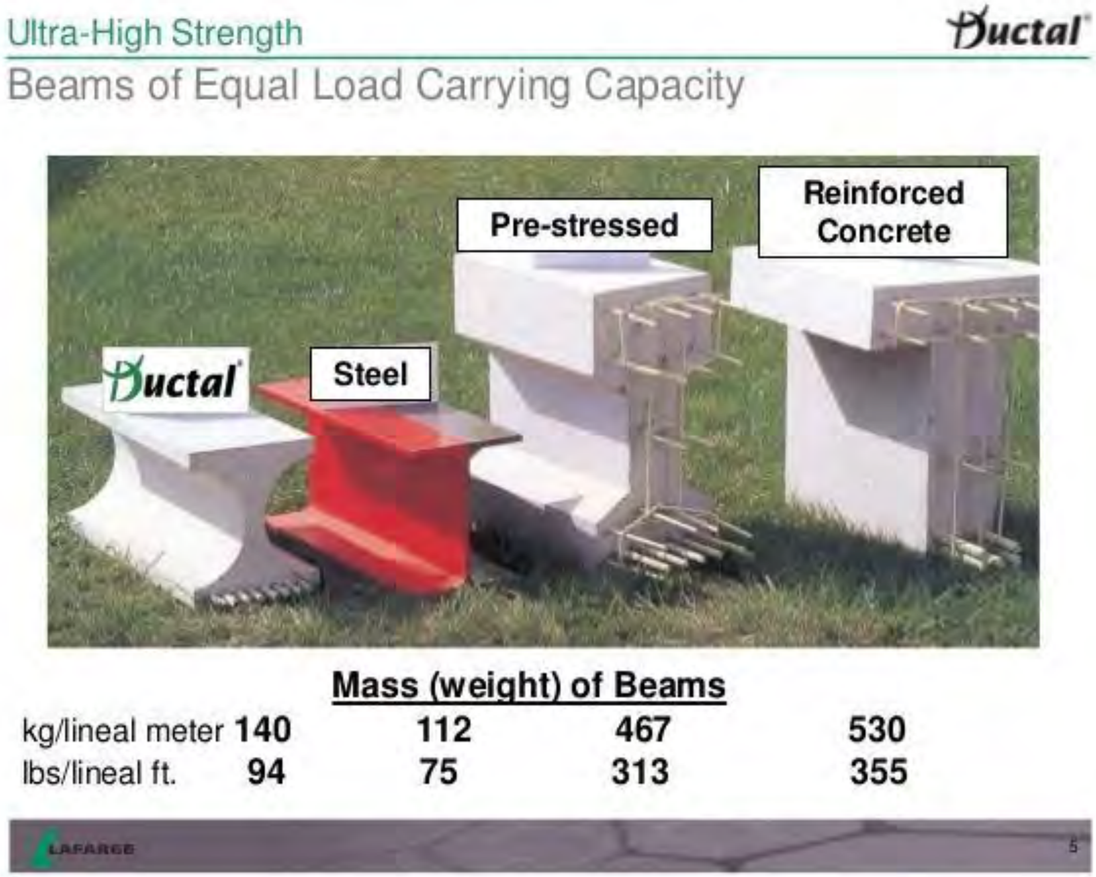

Figure 1: Comparison of Bridge I-Girders with Similar Capacities and Different Materials (ASCE, 2016)

4. Major RPC Construction Projects

The FHWA is currently funding State DoTs to investigate the potential of using proprietary RPC in their new projects. Iowa Department of Transportation utilized available federal funding to construct the first highway bridge in the United States using RPC, known as the Mars Hill bridge. The Mars Hill bridge was constructed in Wapello County, Iowa as a single span bridge using 110 ft. span Iowa Bulb Tee girders. The ductility and high strength of the RPC mixes enabled the designers to use large-number of 0.6-inch pretressing strands and use fewer girders in bridge construction, which expedited the bridge construction process (Aaleti, 2011). The Mars Hill RPC bridge is shown in figure 2.

Figure 2: Mars Hill RPC Bridge Constructed in Wapello County, Iowa (Aaleti, 2011)

The success of Mars Hill RPC bridge construction encouraged researchers at the MIT to design an innovative Pi-shaped bridge girder that includes both bridge girder and bridge deck. The full-scale testing of the Pi-girder indicated a reduced torsional capacity due to the slenderness of the girder. The conclusions of this testing program suggested further optimization of the girder dimensions.

The optimization of the Pi-girder at the FHWA labs resulted in a 2nd generation Pi-girders with improved structural strength. The modifications introduced to the original Pi-girder failing the full-scale test included an increased deck thickness and width, increased web (girder) thickness, and decreased web spacing. The refined design of the 2nd generation Pi-girder targets an increased torsional capacity and improved girder serviceability.

The 2nd Generation Pi-girder is design as a modular component. The width of the girder is 100 inches (perpindicular to traffic direction), the depth of the girder is 33 inches, and the thickness of the slab is 4.1 inches. The girder bulb can accommodate up to 16 prestress strands. The afore-mentioned design enables the girder to span for a distance of 87 ft. without violating any of the AASHTO LRFD Bridge Design Specifications. The span-to-depth ratio of the 2nd generation Pi-girder is 31:1, which allows for material savings, lighter structure, and minimize the need to heavy construction equipment. The 2nd generation Pi-girder is shown in Figure 3.

Figure 3: MIT Pi-Girder Fabricated Using RPC Proprietary Mixes (FHWA-HRT-09-069)

5. Summary and Conclusions

Reactive Powder Concrete (RPC) is introduced to the US construction market as a new type of concrete with superior mechanical properties. RPC mixes are characterized by compressive strength that exceed 21.7 ksi, which enables the design and fabrication with girders with high span-to-depth ratios. Due to the granular high packing order, voids ratios are minimized and RPC mixes have superior long-term performance due to its capability to resist freeze and thaw cycles, in addition to its high chloride resistance.

In recent projects, the FHWA incorporated RPC mixes in bridge construction. The first highway bridge fabricated using RPC mixes was built in Wapello County, Iowa. The high ductility of RPC mixes enabled researchers at the MIT to develop a new Pi-girder that was used in the accelerated construction of Buchanan County bridge in Iowa. Current research is focused on developing newer generations of economic RPC mixes to increase its market share in the US construction market.

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