Development and Applications of Ultra-high Performance Concrete in Bridge Engineering

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Abstract: Ultra-high Performance Concrete (UHPC) is a new type of cement composites, which attracts extensive attention and is applied to bridge engineering area, on account of its superior mechanical performance and durability. With regard to the development and application of ultra-high performance concrete in bridge engineering, the thesis analyzes its application examples, discusses its limited factors and predicts its application future, based on the preparation methods of UHPC and conclusion on the basic performance of materials. UHPC has gradually applied to bridge engineering at home now, which should become application guidance or technical standard in the future, combined with practical projects to promote the research on the application techniques.

1. Introduction
UHPC, having developed rapidly over past years, is defined as a new type of cement composite material with the compressive strength over 150 Mpa\(^1\)\(^2\), which was called reactive powder concrete (RPC) after being studied successfully by BOUYGUES of France in 1933. It realizes extraordinary mechanical property and durability by using cementing matrix from maximal unit weight method. Compared with traditional concrete, UHPC has a number of advantages: it reaches 150Mpa at least, which is three times stronger than traditional concretes; With superior toughness and fracture energy, its toughness is over 300 times than that of high performance concrete, possessing equal strength to some metals, which makes it have an advantage of excellent structure reliability under overload environment or earthquake\(^3\); UHPC presents superior durability due to its dense system, such as carbon-free, low chloride and sulfate permeability close to zero, and good abrasion resistance etc., which can expand the service life of bridge significantly while reduce the maintenance; A mass of unhydrated cement particles existing in UHPC make cement has the function of self-maintenance in case of cracking\(^3\)-\(^4\). The self weight of UHPC structure is is about one third or second of that of traditional concrete, which decrease dead load. The decline of self weight contributes to enlarging the span of the bridge, which can save material cost and reduce the total project cost. On the other hand, the current practice proves that bridges made by ordinary concrete at present exists intricate technique difficulties, affecting the economic efficiency, safety and the durability of the bridge structure. The reason why these relevant difficulties can’t be solved for a long time is that the self weight of the structure is huge, materials or connection appears static force, and the structure is exhausted to crack. However, it is efficient to solve these problems once UHPC is applied to bridge engineering\(^5\)-\(^7\).
The thesis With regard to the development and application of ultra-high performance concrete in bridge engineering, the thesis analyzes its application examples, discusses its limited factors and predicts its application future, based on the preparation methods of UHPC and conclusion on the basic performance of materials, so as to provide references for the application of UHPC in bridge engineering.

2. Preparation of UHPC and the Basic Property of Materials

2.1 Preparation of UHPC

Theoretically, the preparation of UHPC aims to decline micro-defects of final set cements and the porosity. Thus, there are characteristics as follows while the UHPC is on the mix design: Optimizing the mix design of materials, eliminate coarse aggregate and enhancing the unit weight; Choosing efficient water reducing agent with active component of better compatibility; adding to steel fibre to strengthen the toughness of UHPC and optimizing its mechanical property. In regard to the preparation techniques, a large amount of research has been made at home and abroad. Materials made by UHPC from research institutes are almost the same, but there exists differences in mix proportion, especially the choice of fine aggregate and admixture. Representative mix proportions of UHPC at home and abroad are shown as table 1 [8].

|                | Cement | Silica Fume | Quartz Sand | Fine Aggregate | Steel Fiber | admixture | Superplasticizer | Water |
|----------------|--------|-------------|-------------|----------------|-------------|-----------|------------------|-------|
| Abroad         | 710    | 230         | 210         | 1020           | 40~160      | —         | 13               | 140   |
| Home           | 706    | 180         | 1224        | —              | 170         | 15        | 24               | 180   |

It is required to prepare the slurry after the mix proportion of UHPC is designed. Different from the preparation method of the ordinary concrete, research institutes all set strict mixing procedure, certain time and certain speed at corresponding stage for the purpose of mixing averagely and reducing caking of steel fibre, as UHPC adopts lower water binder ratio and raw materials are mixed with coagulative steel fibre. Vibration platform should be adopted while placing UHPC in order to eliminate the porosity. If there is mixed with steel fibre in the UHPC materials, it can’t be vibrated by vibrator in case of the affecting permutation orientation of fibre and lowering the tensile property. Maintenance of UHPC includes natural curing, water curing, steam curing and high-pressure curing. The experiment indicates that compared with room temperature curing, high-pressure curing can efficiently improve UHPC’s compressive strength, elasticity modulus and durability. When it comes to steam curing with a temperature of 90℃, the compressive strength during 3d curing is 25%-30% higher than that of 28d natural curing [9].

At present, there are mature cases that can be followed with regard to raw material choices, mix proportion designs and maintenance systems, it still needs further research if there is carrying out large-scale production.

2.2 Basic Properties of Materials

2.2.1 Mechanical Properties

Comparison in basic mechanical property among UHPC, HPC and NC is presented in Table 2. The table suggests that as for compressive strength and breaking strength, UHPC has a huge advantage over HPC and NC, which is about 5 to 10 times the strength of NC. Due to the limitation of steel fibre from the interior materials of UHPC, the fracture toughness of UHPC is 30 times stronger than that of HPC and NC.

| Types of Concrete | UHPC | HPC | NC |
|-------------------|------|-----|----|
| Compressive strength /(Mpa) | 170-230 | 60-100 | 20-50 |
2.2.2 Durability
The durability of concrete is one of the key factors to decide the life service of bridges, so it is necessary to evaluate the durability of UHPC. There are numerous researches on the durability of UHPC both at home and abroad\cite{11-12}, the durability of UHPC are presented as follows:

(1) Carbonization resistance: BY N.ROUX from France made an experiment that UHPC’s carbonation depth of 90 days is zero in the carbonization box with the CO$_2$ concentration of 100%; Southeast University tested the UHPC by carbonization method, which proved that the carbonization depth of 28 days is 0.25mm. Thus, UHPC has superior carbonization resistance.

(2) Chloride ion penetration resistance: BY N.ROUX from France, as well as Beijing Jiaotong University and Tongji University, has made a large amount of experiments, which indicates that chloride diffusion coefficient of UHPC is 0.2×10\(^{-8}\)cm$^2$/s$^{-1}$.

(3) Abrasion resistance: Municipal Design Institute of Shenzhen affirms that the abrasion resistance of UHPC is superior with an average length of 25.1 mm, according to the Test Method for Abrasion Resistance of Concrete and its Products. BY N.ROUX from France examined the abrasion resistance of C30, C80 and UHPC is respectively 4.0, 2.8 and 1.3 by the test method of abrasion resistance. It comes to a conclusion from above experiments that UHPC possesses extremely excellent abrasion resistance.

2.2.3 Shrinkage Creep
Scholars at home and abroad have carried out a large number of experiment researches on the shrinkage creep features of UHPC. It turns out that shrinkage creep of UHPC is about 0.0008~0.0012, which reaches 80% of total shrinkage amount within 3 days after placing, while nearly accomplished completely after 28 days. The final shrinkage creep coefficient of UHPC reaches 0.3~0.8, which is lower than normal concrete but can be completed within two months. It is available to bridge engineering.

3. Application Examples of UHPC in Bridge Engineering
UHPC is a new creative type of cement composites in the world nowadays. UHPC has applied to high-rise buildings, large-span bridges, hydraulic engineering and defence engineering since it is researched successfully, on account of its excellent mechanical property and durability. UHPC applied to bridge engineering at present has been a heated topic, which is mainly used to beams, arches, wafer-boards, bridge joints and reinforcement of old bridges etc. According to certain statistics, bridges in application of UHPC throughout the world have been over 400 (among which there are 150 bridges used UHPC as main structure material). Part representative bridges of UHPC is listed in the Table 3.

| Names                | Country | Year | Span (m) | Type                    | UHPC Application         |
|----------------------|---------|------|----------|-------------------------|--------------------------|
| Sherbrooke Pedestrian Bridge | Canada  | 1997 | 60       | Space truss girder bridge | 3cm bridge deck main truss concrete |
| Mars Hill Bridge     | USA     | 2006 | 33.5     | Prestressed beam bridge  | I-girder                 |
| Jakway Park Bridge   | USA     | 2008 | 15.6     | Three span simple support bridge | π-girder              |

Table 3 Bridge Examples of UHPC throughout the World
PS 34 Overpass Bridge
Sunyudo Footbridge

Sakata-Mirar Footbridge

Luanbo Gangqu bridge

Zhaqing Mafang Bridge

| Bridge          | Country | Year | Span | girder type                  |
|-----------------|---------|------|------|------------------------------|
| Overpass Bridge | France  | 2005 | 47.4 | Prestressed beam bridge      |
| Sunyudo Footbridge | Korea   | 2002 | 120  | Prestressed half-through arch bridge |
| Sakata-Mirar Footbridge | Japan   | 2002 | 50.2 | Prestressed simply supported beam bridge |
| Luanbo Gangqu bridge | China   | 2006 | 20   | Prestressed simply supported bridge |
| Mafang Bridge   | China   | 2011 | 64   | Simply supported steel composite beam bridge |

The first footbridge of UHPC, Sherbrooke Pedestrian Bridge, was built in Sherbrooke City of Quebec in Canada in 1997, as is shown in Figure 1(a). It adopts the truss structure of steel tube of UHPC with the span of 60 m, while its deck slab uses UHPC deck with the thickness of 3 cm. Besides, the outrigger web adopts the steel tube of UHPC with a diameter of 150 mm, while the bottom chords use precast UHPC sections with the length of 10 m, whose interior sections are not equipped with ordinary steel, assembled with post-tensioned prestressed. Due to the adoption of UHPC, self-weight has declined, which efficiently resists corrosion of sprinkling cryohydrate repeatedly under the severe environment to 30 °C minus in the winter. The bridge was nominated for Nova Award in 1999.

Mars Hill Bridge, the first highway bridge of UHPC built in Iowa of USA in 2006, as shown in Figure 1(b), is a high-grade single span simple support bridge, with the beam length of 33.83 m, the span of 33.53 m and the bridge width of 7.99 m. Its main girder is formed by three prefabricate I-shape beams and the middle of beam is not equipped with non-prestressed reinforced steel, so the shear force is undertaken by the steel fibre of the middle of beam, which simplifies the steel construction. Its beam spacing is 2.92 m with the beam height of 1.07 m, the web thickness of 11.43 m and the depth-span ratio of 1:31.5. Compared with bridges made by normal concrete, Mars Hill Bridge has a smaller size of main girder section but larger case bay, as well as better durability and longer life service.[15] In 2006, the bridge was awarded for the tenth Bridge Competition Award held every two years, which is honored for the Future Bridge.

The first pedestrian bridge in Japan, Sakata-Mirar Footbridge, was built in 2002[16], as is shown in Figure 1(c). Its main girder section is box-girder, adopting the method of precast segmental construction, while the prefabricated beam section is accomplished by precast tensegrity. In 2004, Japan Society of Civil Engineering issued the Construction Companion Draft of UFC Structure Design on the basis of the engineering experience of this bridge as well as the companion of UHPC in France, which regulated the relevant issues of UHPC structure design and companion. Japan continuously constructed a lot of pedestrian bridges since then. For example, both Yamagata Bridge and Tahara Bridge adopted box-girder section as the section form of girder.

In 2011, it is the first time for Mafang Bridge in Zhaqing to combine UHPC with steel box girder into light composite deck, as shown in Figure 1(d). There are 14 spans of 64 m in Mafang Bridge uses simply supported steel box girder of 14 spans of 64 m respectively, which is 919.6 m overall long and 12.1 wide. The bridge floor adopts orthotropic plate of steel material. The bridge experienced several times of maintenance but still existed severe damage in pavement and endurance crack in steel structure since it was built in 1984. The bridge had been complete maintenance by the end of 2011, whose 11th single span has been functioned well so far since it strengthened maintenance with the thickness of 50 mm. At present, there are at least 17 bridges in China using light combination of steel-UHPC bridge floor, which covering various types, such as beam bridge, arch bridge, cable stayed bridge and...
suspension bridge etc. In addition, many bridges in Shanghai applied UHPC to strengthening bridge and bridge joint.

(a) Sherbrooke Pedestrian Bridge;  (b) Mars Hill Bridge  
(c) Sakata-Mirar Footbridge;  (d) Zhaoqing Mafang Bridge

Fig 1 Typical UHPC bridge diagram.

4. The development of UHPC in Bridge Engineering

4.1 The Prospect of UHPC in Bridge Engineering

That UHPC material possesses excellent mechanical property and durability can make longer span, smaller component, more convenient construction, shorter construction time and less harmful effect on environment. Its superior durability can largely reduce the maintenance cost of late period, which is beneficial to expand life service of bridge. As more researches about UHPC’s preparation techniques, matching ratio calculation, material features, structure features and structure design method are developed, it forms a set of technique standards and regulated compile, as well as declines the material cost of UHPC. UHPC materials will be widely used in the bridge engineering.

Nowadays, Ministry of Housing and Urban-Rural Development as well as Ministry of Industry and Information Technology issued the Some Suggestions on Promoting High Performance Concrete by Ministry of Housing and Urban-Rural Development as well as Ministry of Industry and Information Technology. It points out that high performance concrete should be promoted rapidly, which has a profound effect on strengthening energy conservation and emission reduction, preventing air pollution, increasing the engineering quality, improving the durability of engineering structure and reducing the embedded cost of engineering life service. Research scholars in China have made massive application researches of UHPC in the engineering, which has made a series of achievement[18-23]

The high strength and durability can largely decrease the size of fracture surface with the self weight of 40%~60% of that of normal concrete, so as to improve the spanning capacity of structure, improve
the anti-seismic property and reduce the structure size of lower part. In addition, because of its high self strength, UHPC can largely simplify and even can totally replace normal concrete, which simplifies the construction work, reduce labour cost and improve prefabricated construction. What’s more, UHPC is expected to solve current technique problems of bridge structure, such as fatigue cracking of steel bridge deck, vulnerable pavement, cracking and deflection of traditional prestressed force to concrete box, large self weight of steel-concrete combination, cracking of hogging moment concrete slab, and low assemble ratio of small-middle fabricated span. Thus, it plays a significant role in improving bridge techniques in China, and has a wide application prospect in bridge engineering.

4.2 Limitation of UHPC Application in Bridge Engineering
UHPC has many advantages, but the reason why it can be applied to bridge engineering massively is that there exists some key limitations as follows:

(1) Although UHPC has made great achievement in material mixture ratio and preparation technique, its material properties are sensitive to the quality of raw materials and mixture ratio, that is, even if adopted the same mixture ratio, material properties of UHPC will be affected greatly by subtle differences of various materials. Whereas, it is inevitable to eliminate property differences among materials from place to place because materials are mostly adopted from local places while bridges are being built. Therefore, ideal material property of UHPC must be gained from clear material mixture ratio by experiments but from current mixture ratio data.

(2) It is better to use high-frequency vibratory mixing equipment with adjustable stirring velocity while large-scale UHPC materials are being prepared, for the purpose of ensuring components mixed averagely under the circumstance of low water binder and no caking phenomena of steel fibre. However, this technique of large-scale facility is still immature, which can not ensure large-scale continuous preparation. It is necessary to develop and promote large equipment with high frequency vibratory mixing capability, for a huge amount of materials and continuous placing are needed in the bridge engineering.

(3) UHPC materials need rigid high-temperature maintenance and components should be made and maintained in the precast yard in order to ensure the quality, which limits the usage of current placing structure as well as the choice of bridge pavement methods.

(4) UHPC always uses high dose cement (ranging from 800-1000kg/m3), which causes problems of high energy consumption and high carbon emission. Besides, the cost will increase on account of adding steel fibre and other additions responding to the request of UHPC.

(5) The researches on the property of UHPC have been mature by now, but the researches on the mechanical property of UHPC structure are not enough. The current experiment to the mechanical property of components mostly adopts scale model test, lacking of experimental researches full scale components, which can not be presented completely in scale model test, so as not to predict the property of UHPC in the practical structure.

5. Conclusion
As a new type of cement composites, Ultra-high Performance Concrete (UHPC) possesses superior mechanical performance and durability, having extensive application prospect in bridge engineering. There are a mass of bridges adopted UHPC at home and abroad nowadays, which have various advantages: longer span, smaller component size, more convenient construction and shorter time, while less harmful impact on environment and lower cost of maintenance during the later period but efficiently extending the life service. However, there also exist some theoretical technique problems, which limit the extensive application of UHPC to the bridge engineering. With the development of researches on its preparation techniques, matching calculation, material features, structure features and construction designing method and so on, as well as the improvement of technique standard and the decline of UHPC cost, UHPC will be applied to bridge engineering extensively in the future.
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