Research and Applications of Ultra-high Performance Concrete

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Unprecedented infrastructure construction!
In the next 20 to 30 years, there are a large amount of infrastructures to build or rebuild! This requires concrete has high strength, good toughness and durability!
## Historic Developments of UHPC

<table>
<thead>
<tr>
<th>Year</th>
<th>Author(s)</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>Yudenfreund et al</td>
<td>Low porosity paste with strength of 230 MPa</td>
<td>Ultra-fine cement, vacuum mixing, low water-to-cement ratio</td>
</tr>
<tr>
<td>1972</td>
<td>Roy et al</td>
<td>Low porosity paste with compressive strength of 510 MPa</td>
<td>Very low water to cement ratio (0.08) and hot-press method</td>
</tr>
<tr>
<td>1981</td>
<td>Bache, Young et al.</td>
<td>Densified Small Particles (DSP)</td>
<td>Improved particle packing; use of microsilica; use of superplasticizers</td>
</tr>
<tr>
<td>1984</td>
<td>Lankard, Naaman</td>
<td>Slurry Infiltrated Fiber Concrete (SIFCON)</td>
<td>Fine sand mortar with high volume fractions of steel fibers (8% - 15% by volume)</td>
</tr>
<tr>
<td>1987</td>
<td>Bache</td>
<td>Compact Reinforced Concrete (CRC)</td>
<td>Concrete with high volume of steel fibers used with reinforcing bars</td>
</tr>
<tr>
<td>1992</td>
<td>Li, Wu</td>
<td>Engineered Cementitious Composites (ECC)</td>
<td>Mostly mortar with synthetic fibers; strain-hardening behavior in tension</td>
</tr>
<tr>
<td>1993</td>
<td>Richard, Cheyrezy</td>
<td>Reactive Powder Concrete (RPC)</td>
<td>Paste and concrete; heat and pressure curing; particle packing</td>
</tr>
<tr>
<td>1993</td>
<td>De Larrard</td>
<td>Ultra-High Performance Concrete (UHPC)</td>
<td>Optimized material with dense particle packing and ultra fine particles</td>
</tr>
</tbody>
</table>
Characteristics of RPC/UHPC

- Reactive powder concrete (RPC) /UHPC is characterized by high binder content, very low water-to-cement ratio, use of silica fume, fine quartz powder and superplasticizer and/or fine ductile fibers.

- UHPC is a new type of cement-based materials with compressive strength of 150(100)MPa, excellent durability and proper ductability.

<table>
<thead>
<tr>
<th>Item</th>
<th>RPC 200</th>
<th>RPC 800</th>
<th>HPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (MPa)</td>
<td>170-230</td>
<td>490-680</td>
<td>60-100</td>
</tr>
<tr>
<td>Flexural strength (MPa)</td>
<td>25-60</td>
<td>45-102</td>
<td>6-10</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>62-66</td>
<td>65-75</td>
<td>30-40</td>
</tr>
<tr>
<td>Fracture Energy (J/m²)</td>
<td>20000-40000</td>
<td>1200-2000</td>
<td>140</td>
</tr>
</tbody>
</table>
Researches on Very High Performance Concrete in China

- Hunan University published first Chinese paper on Ultra-high strength concrete in the 80’s.
- Several universities started researches on UHPC in the middle of 90’s: Hunan University, Southeast University, Beijing Jiaotong University, Tsinghua University, etc.
- National Science Foundation of China (NSFC) has funded more than 50 projects on UHPC/RPC, including three key projects.
- More than 1000 papers on RPC/UHPC have been published in Chinese journals.
- Hunan University: 8 NSFC projects (including one key), 3 PhD students, 40 master students, 17 patents, 120 journal papers.
Books and Standards on UHPC in China

- The standard specifies definition, raw materials, classification, production, curing, testing methods and inspection of UHPC;
- A few universities are working on local design codes for UHPC.
Design Principles of UHPC

- Reduction in porosity
- Improvement in microstructure
- Enhancement in homogeneity
- Increase in toughness
Principles for UHPC - Reduction in porosity

Balshin’s Equation:
\[ \sigma = \sigma_o \cdot (1 - P)^A \]

Ryshkevitch’s Equation:
\[ \sigma = \sigma_o \cdot \exp(-B \cdot P) \]

Schiller’s Equation:
\[ \sigma = D \cdot \ln\left(\frac{P_o}{P}\right) \]

and Hasselmann's Equation:
\[ \sigma = \sigma_o \cdot (1 - AP) \]
Principles for UHPC - Reduction in porosity

\[ P(D_i) = \frac{D_i^q - D_{\text{min}}^q}{D_{\text{max}}^q - D_{\text{min}}^q} \]

\[ \text{RSS} = \sum_{i=1}^{n} \left[ P_{\text{mix}}(D_i) - P_{\text{tar}}(D_i) \right]^2 \rightarrow \text{min} \]

Where:
- \( P(D_i) \) is a fraction of the total solids being smaller than size \( D_i \);
- \( D_i \) is the particle size (μm),
- \( D_{\text{max}} \) is the maximum particle size (μm)
- \( D_{\text{min}} \) is the minimum particle size (μm) respectively,
- \( q \) is the distribution modulus=0.23
- \( P_{\text{mix}} \) is the composed mixture, and
- \( P_{\text{tar}} \) is the target grading calculated from Eq. (1).
Principles for UHPC - Reduction in porosity

Branch chain  Steric hindrance

Cement particles

agglomerated  dispersed  surface increase

17%
22%
27%
33%
Principles for UHPC - Improvement in microstructure

Cement matrix in conventional concrete

UHPC room curing

Steam curing 10h

Steam curing 48h

Autoclave curing
Principles for UHPC - Improvement in microstructure

ITZ in Conventional Mortar

Steam curing 48h

Room temperature curing

Steamed
Principles for UHPC - Increase in toughness
Typical UHPC mixture proportion

- Cement: 710 kg/m³
- Silica fume: 230 kg/m³
- Sand: 210 kg/m³
- Quartz powder: 1020 kg/m³
- Fiber: 40-160 kg/m³
- Superplasticizer: 13 kg/m³
- Water: 140 kg/m³
Cementing Components for UHPC

- GGBS
- Metakaolin
- Nano-CaCO₃
- Nano-SiO₂
- Limestone powder
- Rice husk ash
Properties of UHPC

Properties

Mechanical
- Static Strengths
- Dynamic properties
- Fiber-matrix bond properties

Dimensional stability
- Autogenous Shrinkage
- Drying Shrinkage
- Creep

Durability
- Permeability
- Frost action
- Carbonation resistance
Fiber-matrix bond properties

- Samples with 15-25% silica fume had the optimal bond properties.
- Maximum bond strength of 3.5 MPa can be obtained under normal room temperature curing.
ITZ Microstructure Development

BSEM images of U20 samples with an embedded fiber

Compressive strength

- **Compressive strength (MPa)**

  - **w/b**
    - 3d
    - 7d
    - 28d
    - 90d

- **Silica fume content (%)**
  - 3d
  - 7d
  - 28d
  - 90d

- **Quarze powder (%)**
  - 3d
  - 7d
  - 28d
  - 90d

- **Sand-to-cementitious ratio**
  - 3d
  - 7d
  - 28d
  - 90d
Compressive strength - fiber content and shape

- **Compressive strength (MPa)**
  - Steel fiber content (%)
  - Time: 3d, 7d, 28d, 90d

- **Flexural strength (MPa)**
  - Steel fiber content (%)
  - Time: 3d, 7d, 28d, 90d

- **Steel fiber shapes**
  - Straight
  - Corrugated
  - Hooked-end

Graphs showing the relationship between compressive and flexural strength with varying steel fiber content and shape over time.
Compressive strength - hybrid steel fiber
Stress-Strain Relationship

(a) L0S0  
(b) L2S0  
(c) L1.5S0.5
(d) L1S1  
(e) L0.5S1.5  
(f) L0S2
Mechanical Properties of UHPC

破坏形态

➢ UHPC的轴压破坏形态可能为剪切破坏或劈裂破坏，未掺钢纤维时，为劈裂破坏，当钢纤维总体积掺量为2%且长纤维体积掺量高于1%时，为剪切破坏，当钢纤维总体积掺量为2%且长纤维体积掺量小于或等于1%时，为劈裂破坏；
Constitutive Relationship

Upside:

\[ f = f_0 \left[ \frac{\beta (\frac{\varepsilon}{\varepsilon_0})}{\beta - 1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^\beta} \right] \]

其中：\[ \beta = \frac{1}{1 - \frac{f_0}{\varepsilon_0 E}} \]

Downside:

\[ f = f_0 \left[ \frac{k_1 \beta (\frac{\varepsilon}{\varepsilon_0})}{k_1 \beta - 1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^{k_2 \beta}} \right] \]

Different Relationships of UHPC with Hybrid Fiber:

Peak stress = 99.014 + 12.713V_l + 2.273V_s - 2.629V_l^2 \quad R^2 = 0.90 \quad (1)

Strain at peak stress = 3.591 + 0.564 V_l + 0.084 V_s - 0.343 V_l^2 \quad R^2 = 0.99 \quad (2)

Elastic modulus = 37.897 + 2.431 V_l + 0.151 V_s - 1.714 V_l^2 \quad R^2 = 0.75 \quad (3)
Bending strength and toughness

Evaluation methods of toughness

- ASTM C1018
- JSCE SF4
- RILEM TC 162-TDF

\[ I_G = \frac{G_{0.8}}{G_m} \]

\[ \eta_5, \eta_{10}, \eta_{20} \]

The \( \eta_5, \eta_{10}, \) and \( \eta_{20} \) are the values by dividing the area up to a deflection of 3, 5.5, and 10.5 times of the first crack deflection by the area up to first crack.
Bending properties - fiber content and shape

### Straight fiber

<table>
<thead>
<tr>
<th>No.</th>
<th>First crack strength (MPa)</th>
<th>First crack deflection (mm)</th>
<th>Peak strength (MPa)</th>
<th>Peak deflection (mm)</th>
<th>Toughness indexes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>19.0</td>
<td>0.30</td>
<td>19.0</td>
<td>0.30</td>
<td>1.00 1.00 1.00</td>
</tr>
<tr>
<td>A1</td>
<td>19.2</td>
<td>0.31</td>
<td>21.7</td>
<td>0.36</td>
<td>4.79 9.08 14.56</td>
</tr>
<tr>
<td>A2</td>
<td>19.3</td>
<td>0.32</td>
<td>27.8</td>
<td>0.53</td>
<td>7.86 14.95 22.05</td>
</tr>
<tr>
<td>A3</td>
<td>19.9</td>
<td>0.33</td>
<td>38.3</td>
<td>0.80</td>
<td>10.17 19.78 27.10</td>
</tr>
</tbody>
</table>

### Corrugated fiber

### Hooked end fiber
Bending properties - hybrid steel fiber

<table>
<thead>
<tr>
<th>No.</th>
<th>Pre-cracking strength (MPa)</th>
<th>Pre-cracking deflection (mm)</th>
<th>Peak strength (MPa)</th>
<th>Deflection at peak stress (mm)</th>
<th>η₅</th>
<th>η₁₀</th>
<th>η₂₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0S0</td>
<td>18.3</td>
<td>0.26</td>
<td>18.3</td>
<td>0.26</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>L2S0</td>
<td>19.1</td>
<td>0.31</td>
<td>30.2</td>
<td>0.54</td>
<td>8.54</td>
<td>15.33</td>
<td>23.06</td>
</tr>
<tr>
<td>L1.5S0.5</td>
<td>19.0</td>
<td>0.30</td>
<td>31.9</td>
<td>0.53</td>
<td>8.63</td>
<td>14.77</td>
<td>21.29</td>
</tr>
<tr>
<td>L1S1</td>
<td>18.7</td>
<td>0.28</td>
<td>24.2</td>
<td>0.49</td>
<td>6.85</td>
<td>12.82</td>
<td>19.25</td>
</tr>
<tr>
<td>L0.5S1.5</td>
<td>18.5</td>
<td>0.27</td>
<td>22.6</td>
<td>0.47</td>
<td>6.53</td>
<td>12.21</td>
<td>18.59</td>
</tr>
<tr>
<td>L0S2</td>
<td>18.4</td>
<td>0.26</td>
<td>20.8</td>
<td>0.36</td>
<td>5.39</td>
<td>10.45</td>
<td>15.60</td>
</tr>
</tbody>
</table>
Dynamic properties - Impact properties

UHPFRC is sensitive to the strain rate. Under the same compressive loading, the sample of UHPFRC matrix was **crushed** while the sample made of UHPFRC with 3% or 4% of steel fibers by volume fraction remained essentially **intact**.
The peak stress increased with the increase of strain rate, showing strain rate effect.

- **L1.5S0.5** mixture had the highest dynamic properties, followed by **L1S1** and **L0.5S1.5** mixtures.
- **L2S0** showed comparable peak stress to **L0S2**.
Autogenous shrinkage of UHPC

**SiCc** fume content

**W/B**

**Fiber content**

**Silica fume content**
### Composition of Quaternary cementitious materials

<table>
<thead>
<tr>
<th>NO.</th>
<th>Cement</th>
<th>Silica fume</th>
<th>Fly ash</th>
<th>Slag</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-1</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N-2</td>
<td>70</td>
<td>30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N-3</td>
<td>70</td>
<td>0</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>N-4</td>
<td>70</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>N-5</td>
<td>85</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N-6</td>
<td>85</td>
<td>0</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>N-7</td>
<td>85</td>
<td>0</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>N-8</td>
<td>70</td>
<td>15</td>
<td>15</td>
<td>0</td>
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<tr>
<td>N-9</td>
<td>70</td>
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<td>N-10</td>
<td>70</td>
<td>0</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>N-11</td>
<td>80</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>N-12</td>
<td>80</td>
<td>10</td>
<td>0</td>
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<tr>
<td>N-13</td>
<td>80</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>N-14</td>
<td>70</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>N-15</td>
<td>77.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Effect of Composition on Autogenous Shrinkage

![Diagram showing the effect of composition on autogenous shrinkage. The graph plots autogenous shrinkage (μm/m) against time (h) for different compositions labeled N1 to N15. The composition triangle on the right shows the relative proportions of cement, slag, and silica fume.]
Effect of Composition on Autogenous Shrinkage

\[ Y_{As_{72}} = Y1 \times 10^3 x_1 + 2 \times 10^4 x_2 + 1.4 \times 10^4 x_3 + 1.2 \times 10^4 x_4 - 2.2 \times 10^4 x_1 x_2 \\
- 1.9 \times 10^4 x_1 x_3 - 1.5 \times 10^4 x_1 x_4 - 7 \times 10^5 x_2 x_3 - 5.2 \times 10^4 x_2 x_4 \\
+ 1 \times 10^5 x_3 x_4 + 8.99 \times 10^5 x_1 x_2 x_3 + 2.3 \times 10^4 x_1 x_2 x_4 + 1.91 \times 10^5 x_1 x_3 x_4 \\
+ 2 \times 10^7 x_2 x_3 x_4 - 2 \times 10^7 x_1 x_2 x_3 x_4 \]
Mitigation of Autogenous Shrinkage by SAP and SRA
Drying shrinkage

Dry shrinkage ($\times 10^{-6}$) vs. Time (h)

- w/b=0.14
- w/b=0.16
- w/b=0.18
- w/b=0.20
- w/b=0.22

Dry shrinkage ($\times 10^{-6}$) vs. Time (d)

- 10%
- 15%
- 20%
- 25%
- 30%

Dry shrinkage ($\times 10^{-6}$) vs. Time (h)

- 0.8
- 1.0
- 1.2
- 1.4
- 1.6

Dry shrinkage ($\times 10^{-6}$) vs. Dry shrinkage (h)

- 0.8
- 1.0
- 1.2
- 1.4
- 1.6
Water permeability and carbonation

W/B < 0.23, the permeability is extremely low; no carbonation could be detected after 28 days of exposure to 20% CO2.
Durability comparison among UHPC, HPC and OC
Compressive Strength of Slag-Based UHPC in Different Environments

![Graphs showing the compressive strength of slag-based UHPC in different environments over time.](image)
Compressive Strength of Fly Ash-Based UHPC in Different Environments
Dimensional Stability of UHPC in Different Environments

- **Outdoor**
- **Water**
- **Seawater**

Graphs showing shrinkage (10^-6) over exposure time in different environments. Each environment has multiple trials labeled as F0, F1, F2, and F3, and K0, K1, K2, and K3.
Mass Change of UHPC in Different Environments
TGA of UHPC at Different Ages in Different Environments

F-0 - 60 Days
- Seawater
- Water
- Outdoor

CH
CaCO₃

F-0 - 720 Days
- Seawater
- Water
- Outdoor

CH
CaCO₃

K-0 - 60 Days
- Seawater
- Water
- Outdoor

CH
CaCO₃

K-0 - 720 Days
- Seawater
- Water
- Outdoor

CH
CaCO₃
SEM Pictures of UHPC at 360 d

Water

Seawater

Water, Inside 5mm

Seawater, Inside 5mm
Microstructure of UHPC at 720 Days in Different Environments

Seawater

Outdoor

Seawater, Inside 5mm

Outdoor, Inside 5mm
UHPC试样在720天后钢纤维表面锈蚀和内部钢纤维情况
Applications of UHPC

Footbridge in Sherbrooke, Quebec, 1997

Shawnessy LRT station in Calgary, Canada
Researches on Very High Performance Concrete in China

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Applications of UHPC in China

- High speed railway/Subway cable ditch system;
- Lightweight composite bridge decks;
- Precast bridge girders/piers;
- Precast assembled bridge;
- High performance grout for different applications.
Applications of UHPC in China

- High speed railway/Subway cable system

- UHPC cover has replaced conventional concrete cable ditch system in high-speed railway in China since 2009;

- 21.4 million m² UHPC has been used in 16,000 km high-speed railway till March 2015;

- A total of 535,000 m³ of UHPC has been used for those;
Applications of UHPC in China

- Lightweight Composite Bridge Deck

Ma Fangshan Bridge

Dongting Lake Bridge
Applications of UHPC in China

- Highway Bridge Girders

- First highway UHPC bridge in China;
- At K34+690 on highway from Shijiazhuang to Cixian highway;
- The bridge has two lanes and width of 8m consisting of three prestressed UHPFRC box girders in the cross-section;
- Designed $f_{cu}=130\text{MPa (100}\times100\times100\text{mm})$ and $E_s=40\text{Gpa (100}\times100\times300\text{mm})$;
- Pressress UHPC girders, prestressed as normal PC girders, erected on the piers and abutments;
Applications of UHPC in China

- Highway Bridge Girders

<table>
<thead>
<tr>
<th>Mixture Proportion of UHPC (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cement</strong></td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>851</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

1. After casting, \( t \geq 6 \text{h}, T \geq 10^\circ\text{C} \text{and} RH \geq 60\%; \)
2. Then steam curing at \( T \geq 90^\circ\text{C} \text{and} RH \geq 95\% \text{ for } 72\text{h} \) (heating rate \( \leq 12^\circ\text{C}/\text{h} \) and cooling rate at \( \leq 15^\circ\text{C}/\text{h} \));
3. \( \geq 7\text{d} \) of natural curing after steam curing;
4. Girders were jointed together by in-situ cast UHPC and cured at \( T=70\pm3^\circ\text{C} \) for 72h.
Applications of UHPC in China

-Fully Precast Assembled Bridge in Changsha

Crossover Bridge in Changsha, China (Jan 8, 2016) (10 hours for assembling)
Applications of UHPC in China

- Precast Assembled Bridge in Changsha

36.8m + 27.6m + 6.4m = 70.8m
Applications of UHPC in China

- Precast Assembled Bridge in Changsha
Applications of UHPC in China

- Precast Assembled Bridge in Changsha

单位：cm
Applications of UHPC in China

- Precast Assembled Bridge in Changsha
Applications of UHPC in China

- Precast Assembled Bridge in Changsha
Applications of UHPC in China

- Precast Assembled Bridge in Changsha
Application of UHPC in China - Grout for Anchor

矮寨大桥 Aizhai Bridge: CFRP Anchor + RPC Grout
Applications of UHPC in China

- Grout for steel-concrete combination

云南六库怒江二桥
Yunnan Liuku Nujiang No.2 Bridge

- 175m+81m steel-concrete composite beam suspension bridge;
- Single tower, single box, 32m wide.
Conclusions

- The main principles for UHPC design include reduction in porosity, improvement in microstructure, enhancement in homogeneity and increase in toughness.

- The compressive, tensile and flexural strengths of UHPC could reach from 200 to 800 MPa, 25 to 150 MPa and 30 to 141 MPa respectively depending on compositions, production process and curing conditions. Heat curing could increase the compressive strength of UHPC.

- Deformed shaped fiber can increase the compressive and flexural strengths and toughness. Use of 1.5% long fiber and 0.5% short fiber can static and dynamic properties.

- The application of heat-curing, incorporation of fibers, and the use of coarse aggregates can decrease the drying shrinkage of UHPC. The permeability coefficient and diffusion coefficient of UHPC are much lower than those of conventional concrete. The 28d carbonation depth of UHPC is very low.

- The freezing resistance of UHPC is better than that of ordinary concrete and high strength concrete. The fire resistance of UHPC is better than that of ordinary concrete and HPC.
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THANK YOU!

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