Ultra-high Performance Concrete in Construction

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Contents

A. Ultra-high performance concrete (UHPC)
B. Microstructure, compositions and properties
C. Construction applications
D. Summary
A. Ultra-High Performance Concrete (UHPC)
Concrete: the material making the modern world

WE ARE LIVING IN A MATERIAL WORLD
How cement, iron, and other stuff makes modern life possible.

Have You Hugged a Concrete Pillar Today?

By Bill Gates | June 12, 2014

Source: http://www.gatesnotes.com
Innovations in concrete technology

Eddystone Lighthouse, UK, 1759
(Source: Geological Society of London)

Stone House, Hong Kong, 1923
(Source: Wikimedia Commons)
ACI Excellence in Concrete Construction, 2015

Curtesy by American Concrete Institute
Properties of concrete and its lifespan

- Concrete production and supply
  - Consistency
  - Early strength
  - Volume change
  - Drying shrinkage and creep
  - Sorptivity or water permeability
  - Chloride permeability
  - AAR/ASR and other durability properties

- Carbon footprint

- Construction
  - Stiffening
  - Characteristic strength

- Operation, maintenance, rehabilitation
  - 90 days
  - 28 days
  - 7 days
  - 1 day
  - 3 hrs
  - 12 hrs
  - 15 mins

- Reuse, recycling, disposal
  - Time (year)
  - 1000
  - 120 yrs
  - 50 yrs
  - 100
  - 10
High-performance concrete (HPC)

- Tailor-made properties to improve the efficiency in use

Courtesy of C. Krämer, Uni. of Siegen, Germany
Ultra-high performance concrete (UHPC)

• UHPC defined by Federal Highway Administration, U.S. (2011):
  – cementitious composite material composed of an optimized gradation of granular constituents
  – water-to-cementitious materials ratio less than 0.25
  – high percentage of discontinuous internal fiber reinforcement
  – compressive strength greater than 150 MPa
  – sustains post-cracking tensile strength greater than 5 MPa
  – discontinuous pore structure that significantly enhancing durability

• UHPC defined in Europe (2012):
  – Steel fiber reinforced cementitious composite
  – characteristic unconfined compressive strength from 150 ~ 250 MPa
  – contains steel fibers to achieve ductile behavior in tension
  – possibly overcomes or minimizes the use of active/passive reinforcement
  – high binder content which leads to absence of any capillary porosity
  – direct tensile strengths generally higher than 7 MPa
UHPC (continued)

- UHPC defined in China (2016):
  - cementitious composite material that satisfies compacted packing requirements of granular constituents
  - compressive strength between 120~200MPa
  - tensile strength between 7~12MPa
  - elastic modulus between 40~60GPa
  - other fresh/hardened concrete property requirements

- Other names since 1972:
  - Macro Defect Free cement (MDF), U.K., 1981
  - Densified System containing homogeneously arranged ultra-fine Particles (DSP), Denmark/U.S./Canada, 1980’s
    - Compact Reinforced Composite (CRC), Denmark, 1987
    - Ultra-High Performance Fiber Reinforced Concrete (UHPFRC), U.S., 1987
    - Reactive Powder Concrete (RPC), France, 1995
    - Special Industrial Concrete (Beton Special Industriel, BSI), Germany, 1990’s
  - Slurry Infiltrated Fibre Concrete (SIFCON), U.S., 1980’s
  - Engineered Cementitious Composite (ECC), U.S., 1992
  - Ultra-High Strength Concrete/Super-High Strength Concrete
HPC and UHPC classified by strength

“Concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices.”

- American Concrete Institute, January 2013

<table>
<thead>
<tr>
<th></th>
<th>Normal concrete</th>
<th>High-performance concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grade strength by cube (MPa)</td>
<td>High strength</td>
</tr>
<tr>
<td></td>
<td>≤ 50</td>
<td>55 - 80</td>
</tr>
<tr>
<td></td>
<td>Water/cement ratio</td>
<td>≥ 0.45</td>
</tr>
<tr>
<td>Chemical admixtures</td>
<td>Not required</td>
<td>Superplasticizer</td>
</tr>
<tr>
<td>Mineral admixtures</td>
<td>Not required</td>
<td>PFA/GGBS</td>
</tr>
<tr>
<td>Chloride permeability (Coulombs)</td>
<td>&gt; 2,000</td>
<td>500 – 2,000</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>Not required</td>
<td>Not required</td>
</tr>
<tr>
<td>Sustained tensile strength (MPa)</td>
<td>Not required</td>
<td>Not required</td>
</tr>
</tbody>
</table>

B. Microstructure, Compositions and Properties
Microstructure of concrete

Coarse aggregate

Interfacial transition zone

Paste
- fine aggregate
- hydrated & unhydrated cementitious material particles
- water
- air

Entrained air void

Free water

By volume: 68% Aggregate + 32% Cement & Water & Air

By weight: 26% Cement & Water + 74% Aggregates

Typical UHPC solution

Raw material for premix:
- Cement, sand, secondary cementitious materials, nano-carbon tubes (or other ingredients kept secret), etc.

Fibers:
- Metallic
- Organic
- Glass
- Polymer

Pre-blended UHPC dry mix:

Admixtures
- Superplasticizer
- Accelerators
- Anti-shrinkage admixtures

Ready-mixed UHPC for placing

Source: Ductal® Solutions, Thorp UK, September 12th, 2016
Weight composition of UHPC with compressive strength of 200 MPa

<table>
<thead>
<tr>
<th></th>
<th>Sauzeat et al</th>
<th>Aitcin and Richard</th>
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<tbody>
<tr>
<td>Cement</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Water</td>
<td>0.28</td>
<td>0.15</td>
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<tr>
<td>Superplasticizer</td>
<td>0.06</td>
<td>0.044</td>
</tr>
<tr>
<td>Silica fume</td>
<td>0.33</td>
<td>0.25</td>
</tr>
<tr>
<td>Fine sand</td>
<td>1.43</td>
<td>1.1</td>
</tr>
<tr>
<td>Quartz flour</td>
<td>0.3</td>
<td>N.A</td>
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</tbody>
</table>


- Less use of concrete
- Slimmer and lighter structures
- Faster construction program
- Lower life-cycle cost
## General material properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Plain UHPC</th>
<th>UHPC</th>
<th>Ductal®</th>
<th>Dura®</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $D$ (kg/m$^3$)</td>
<td>2620</td>
<td>2650</td>
<td>2300±100</td>
<td>2425±25</td>
</tr>
<tr>
<td>Strength, $f$ (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- $f_{cu, c, 100mm}$</td>
<td>159</td>
<td>170</td>
<td>144</td>
<td>160-180</td>
</tr>
<tr>
<td>- $f_{cy, c, \phi100x200mm}$</td>
<td>133</td>
<td>147</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>- $f_{cy, split tensile, \phi150x300mm}$</td>
<td>10</td>
<td>7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- $f_{p, flexural,100x100x500mm}$</td>
<td>-</td>
<td>-</td>
<td>15</td>
<td>20-30</td>
</tr>
<tr>
<td>- $f_{p, tensile, 100x100x500mm}$</td>
<td>-</td>
<td>-</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>Elastic modulus, $E_c$ (GPa)</td>
<td>55</td>
<td>55</td>
<td>45</td>
<td>45-50</td>
</tr>
<tr>
<td>Chloride permeability ($10^{-12}$m$^2$/s)</td>
<td>-</td>
<td>-</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>Rapid chloride permeability (C)</td>
<td>22</td>
<td>96</td>
<td>-</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>
Specific strength vs packing density

Combined Particle Size Distribution of Different Concrete Mixes

- C45 75-150mm slump
- C100 650mm slump flow HPC
- C150 600mm slump flow UHPC
- Modified Andreassen: q=0.22
- Modified Andreassen: q=0.20
- Modified Andreassen: q=0.13
Stress-strain relationship

Normal Grade 45 MPa concrete (indicative)

- Plain UHPC
- UHPC
- Granite 1
- Granite 2
Durability and life-cycle cost

**Note:**
1. The structural element and exposure condition under investigation 1x1x10m pier located in marine tidal zone.
2. Rapid chloride penetration test results of grade 45, 100 and 150MPa concrete are 1,250, 134 and 22 coulombs, respectively.
Lifespan of UHPC vs normal HPC

- Reusable
- Nearly free from maintenance
- Reuse, recycling, disposal
- Operation, maintenance, rehabilitation

Concretes Life Cycle

Concrete production and supply
- Much more challenging
- Much faster
- Characteristic strength
- Reusable
- Nearly free from maintenance
- Reuse, recycling, disposal
- Operation, maintenance, rehabilitation

Performance

- Similar
- 4 times faster
- More than 3 times higher

- Both lower depending on mixture
- Both no

Drying shrinkage and creep
Sorptivity or water permeability
Chloride permeability
AAR/ASR and other durability properties
Ductility

Note: The comparison is based on a typical UHPC against common local grade 45MPa marine concrete.
UHPC conferences and products

- International Symposium on UHPC and Nanotechnology for High Performance Construction Materials (HiPerMat) at Uni. of Kassel, Germany

- Engineering Research and Development Center, US Army Corps of Engineers
  - Cementitious material
  - Compressive strength > 138MPa
  - No coarse aggregates

- Commercial products:
  - Ductal®, France
    - Reactive Powder Concrete (RPC) by Lafarge
    - Generic brand designation RPC200, RPC400, etc.
  - Densit® and Hi-Con®, Denmark
    - Compact Reinforced Composite (CRC)
  - Hunan University & Hunan Mingxiang Science and Technology Ltd., China
    - RPC, Compressive strength 120 - 200MPa
  - DURA®, Malaysia: RCP
  - ceEntek, Singapore: RCP with nano materials
C. Construction Applications
Construction application of UHPC

Non-structural products:
(Liquid containers; architectural features; repair materials, etc.)

Infrastructures
(Bridge girder, deck, box girder, U-trough, pier, jetty, pile, connections, anti-blast concrete structures, nuclear plant, water retaining structures, etc.)

Buildings
(Precast products like façade, prefabricated bathroom wall/slab, beam, column, etc.)
Innovations in concrete bridge construction

14m span Pont de Chazelet, France, 1875 (Source: Se connaitre)

Max 72m span Pont du Veudre, France, 1911-1944 (Source: Association Eugene Freyssinet)

60m span Sherbrooke Pedestrian Overpass, Quebec, Canada, 1997 (Source: fhwa.dot.gov)

120m span Footbridge of Peace, Seoul, South Korea, 2002 (Source: fhwa.dot.gov)
The 1st UHPC bridge in China

- 6.6m wide, 70.8m long in three spans (27.6, 36.8 & 6.4m) and 5.4m high
- Slab thickness 0.2m
- Depth-span ratio 1/28

- Unit weight of main beam: 0.855t/m²
- Max compressive strength 200MPa
- Precast bridge
- Fabricated in 10 hours on 8 Jan 2016

Source: http://news.sciencenet.cn/htmlnews/2016/9/355715.shtm
UHPC bridges in North America

UHPC bridges in Malaysia

Museum of European and Mediterranean Civilizations and Ductal® UHPC

Source: Ductal® Solutions, Thorp UK, September 12th, 2016
Prefabricated bathroom unit
Various applications

Upper left photo: Brian H. Green. Ultra high performance concrete (UHPC): What it is, its history and why we care? (Sep 2011)
Lower left and right photo: Ductal® Solutions, Thorp UK, September 12th, 2016
Current status

- Tsinghua University. National standard reactive powder concrete (Draft), China (2013).
Common challenges in UHPC construction

• Academic: lack of local scientific research and development
• Technological:
  – Lack of code of practice for structural use of UHPC
  – Relatively short history of worldwide field application
  – Lack of data about UHPC made from locally available raw materials
• Economic:
  – Lack of localized justification on economic benefits
  – High investment in manufacturing facility
  – High material cost
  – High cost for verification/demonstration trials
• Social:
  – Lack of demands for advanced concrete technology
  – Lack of financial and regulatory authority’s support to pilot application
  – Lack of common understanding, knowledge and experiences in local engineering society
D. Summary
Summary

• UHPC has been developed for more than 40 years and used in North America, Europe, Japan, China.

• Due to proved benefits, applications of UHPC in building or infrastructure projects are accelerating in recent years. In the near future, the use of UHPC in both precast and cast in-situ will keep increasing.

• Existing research data reveals that properly designed and manufactured UHPC can achieve a compressive strength well above 150MPa and such potential could notably minimize or eliminate the use of steel reinforcement, further helping achieve a more sustainable built environment.

• In Hong Kong, research and pilot project implementation is needed to harvest the sustainable, economic and social benefits of UHPC.
Thank You