Research and Applications of Ultra-high Performance Concrete

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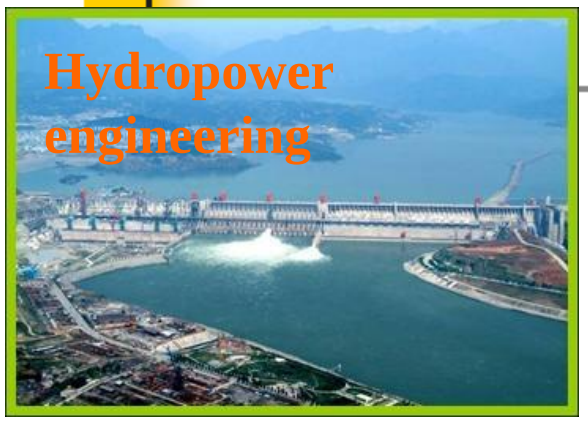
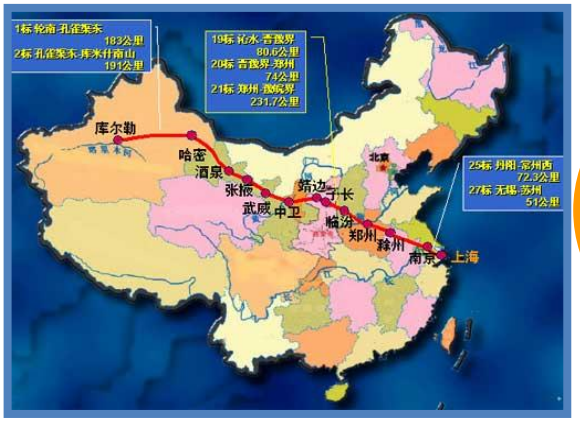




Unprecedent infrustructure construction !

Background

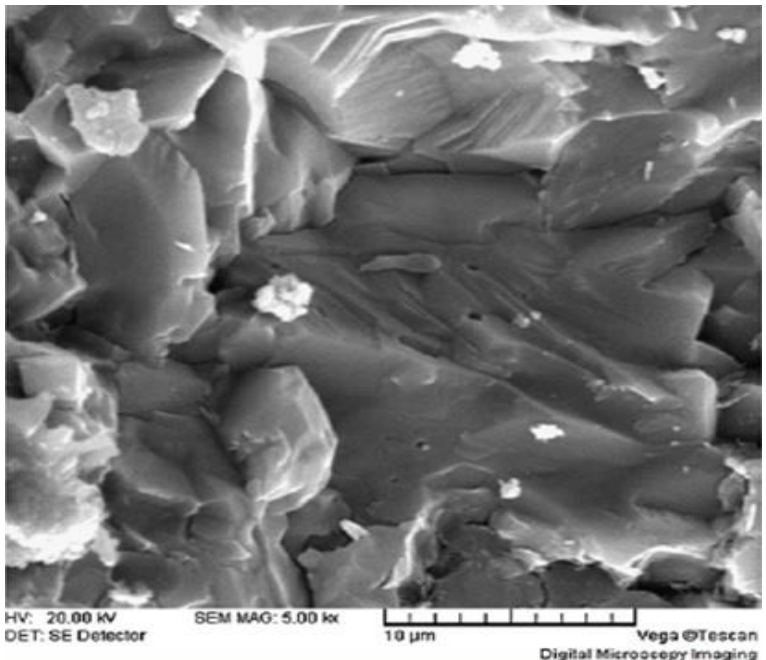
In the next 20 to 30 years, there are a large amount of infrastructures to build or rebuild! This requires concrete has high strength, good toughness and durability!

Historic Developments of UHPC

Year	Author(s)	Name	Description
1972	Yudenfreund et al	Low porosity paste with strength of 230 MPa	Ultra-fine cement, vacuum mixing, low water-to-cement ratio
1972	Roy et al	Low porosity paste with compressive strength of 510 MPa	Very low water to cement ratio (0.08) and hot-press method
1981	Birchall et al.	Micro-Defect-Free (MDF)	Addition of polymer; bending strength up to 30 MPa.
1981	Bache, Young et al.	Densified Small Particles) (DSP)	Improved particle packing; use of microsilica; use of superplasticizers
1984	Lankard, Naaman	Slurry Infiltrated Fiber Concrete (SIFCON)	Fine sand mortar with high volume fractions of steel fibers (8% - 15% by volume)
1987	Bache	Compact Reinforced Concrete (CRC)	Concrete with high volume of steel fibers used with reinforcing bars
1992	Li, Wu	Engineered Cementitious Composites (ECC)	Mostly mortar with synthetic fibers; strain-hardening behavior in tension
1993	Richard, Cheyrezy	Reactive Powder Concrete (RPC)	Paste and concrete; heat and pressure curing; particle packing
1993	De Larrard	Ultra-High Performance Concrete (UHPC)	Optimized material with dense particle packing and ultra fine particles

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.



Item	RPC 200	RPC 800	HPC
Compressive strength（MPa）	170-230	490-680	60-100
Flexural strength（MPa）	25-60	45-102	6-10
Elastic modulus（GPa）	62-66	65-75	30-40
Fracture Energy（J/m^2）	20000-40000	1200-2000	140

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

- A Chinese book entitled "Reactive Powder Concrete" published in 2013;
- A Chinese book entitled "Ultra high performance Cement-based Materials" published in 2015;
- Chinese National Standard GB/T 31387-2015 "Reactive Powder Concrete" issued in 2015;
- 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.

ICS 91.100.30
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GB

中华人民共和国国家标准

GB/T 31387—2015

工程试验检测群：94527577

活性粉末混凝土

Reactive powder concrete

2015-02-04 发布　　2015-11-01 实施

中华人民共和国国家质量监督检验检疫总局
中国国家标准化管理委员会　发布

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:

$$\sigma = \sigma_o.(1 - P)^A$$

Ryshkevitch's Equation:

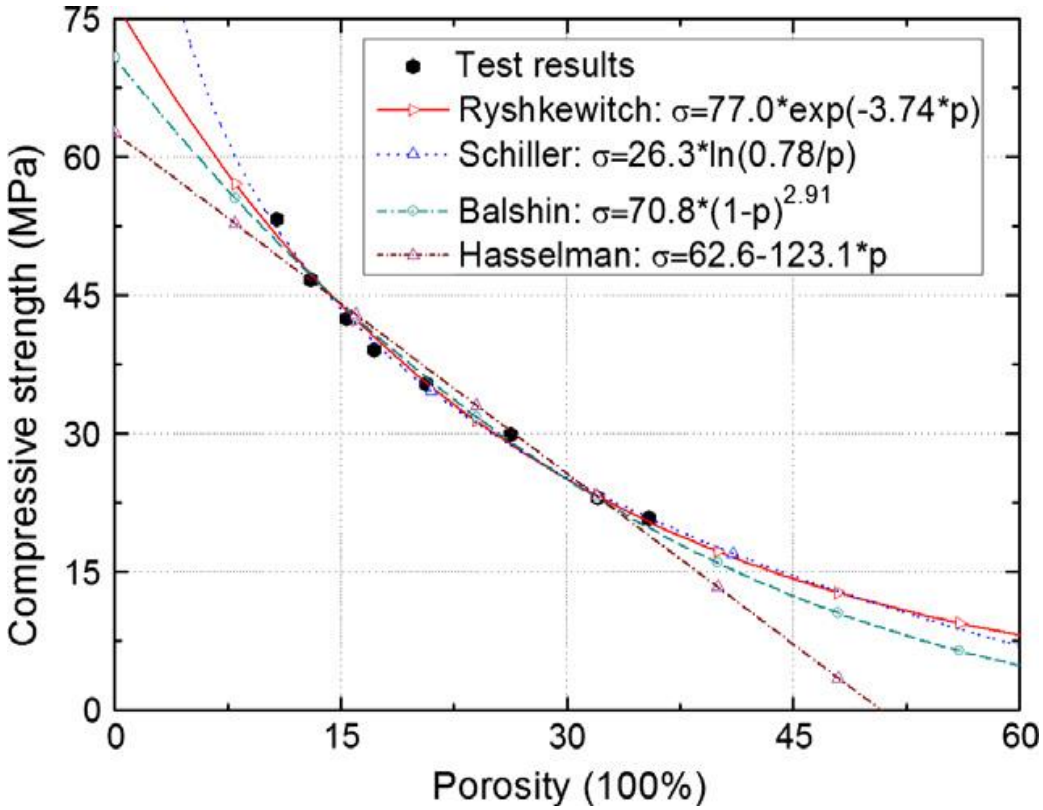
$$\sigma = \sigma_o.\exp(-B.P)$$

Schiller's Equation:

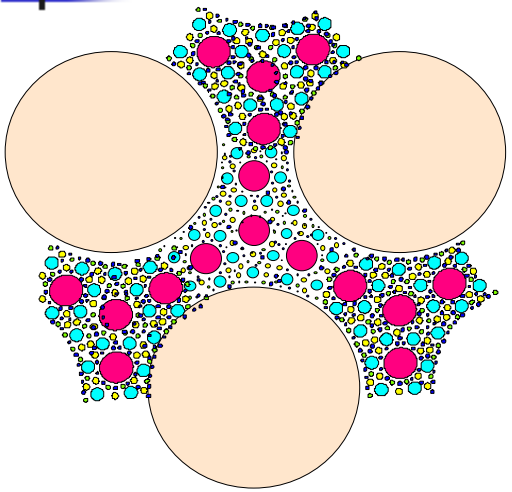
$$\sigma = D.\ln(\frac{P_o}{P})$$

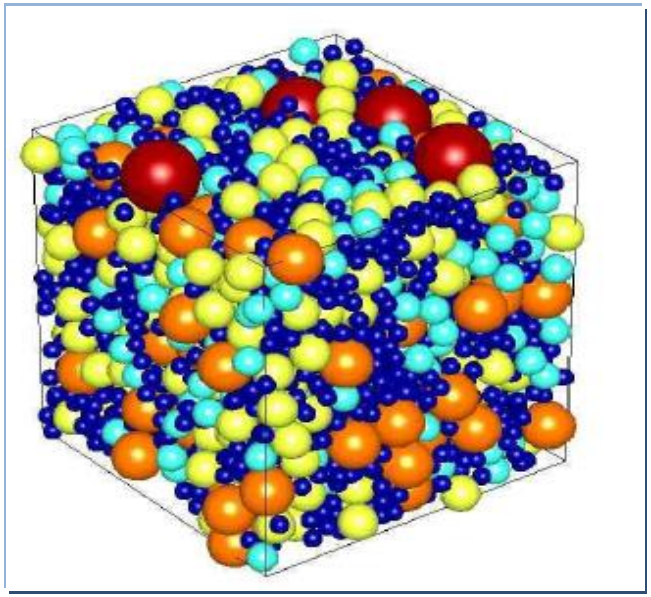
and Hasselmann's Equation:

$$\sigma = \sigma_o.(1 - AP)$$



Principles for UHPC-Reduction in porosity





Close packing model

$$P(D_i) = \frac{D_i^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q}$$

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

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_{max} is the maximum particle size (μm)

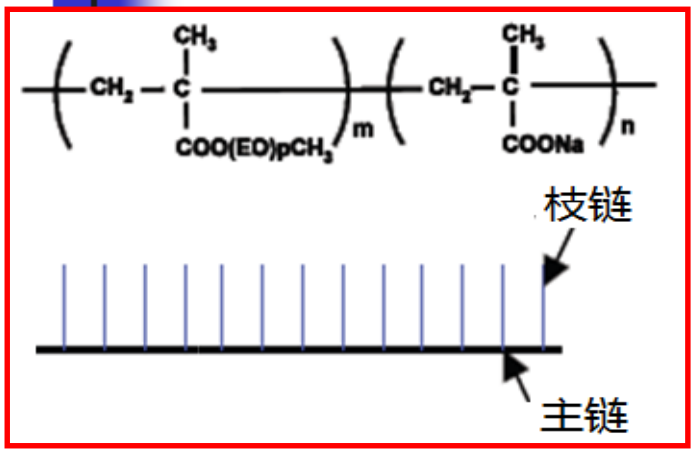
D_{min} is the minimum particle size (μm) respectively,

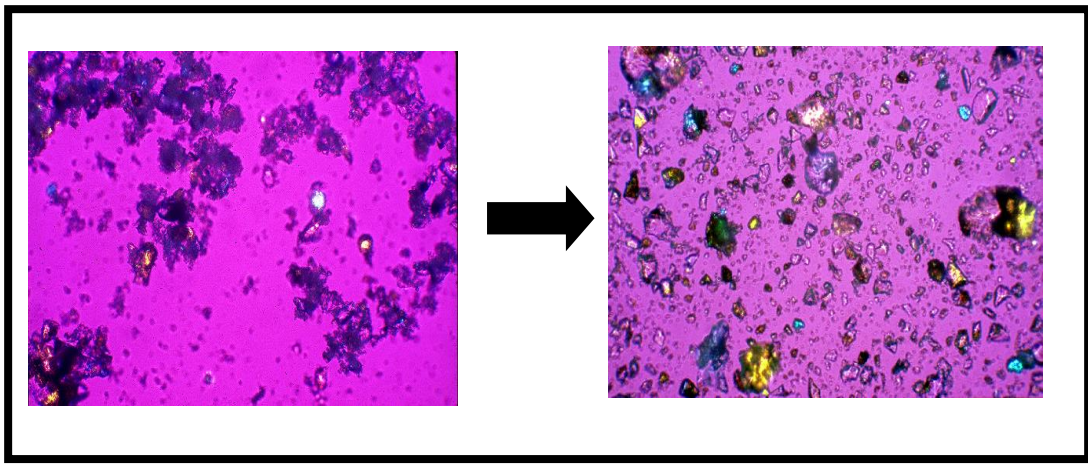
q is the distribution modulus=0.23

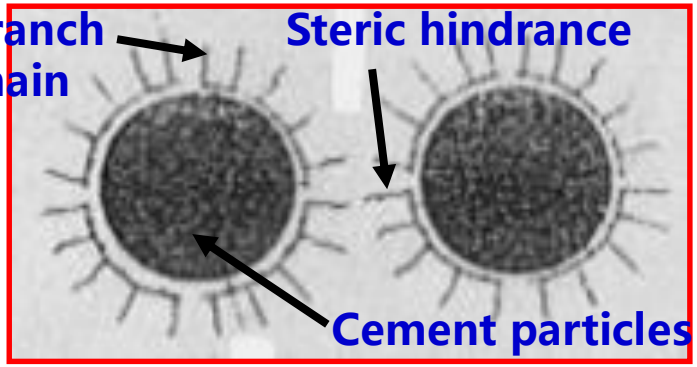
P_{mix} is the composed mixture, and

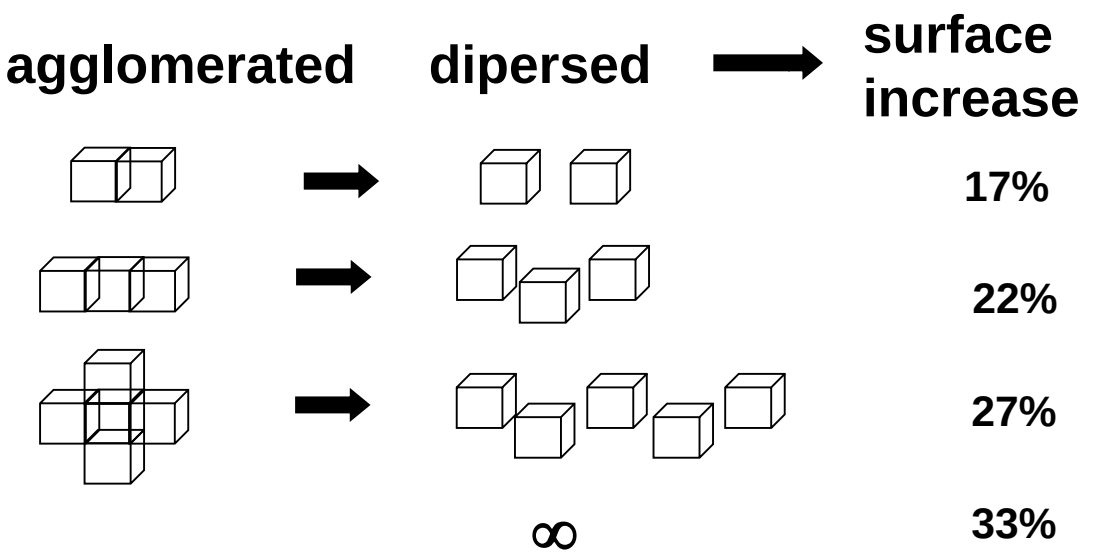
P_{tar} is the target grading calculated from Eq. (1).

Principles for UHPC-Reduction in porosity

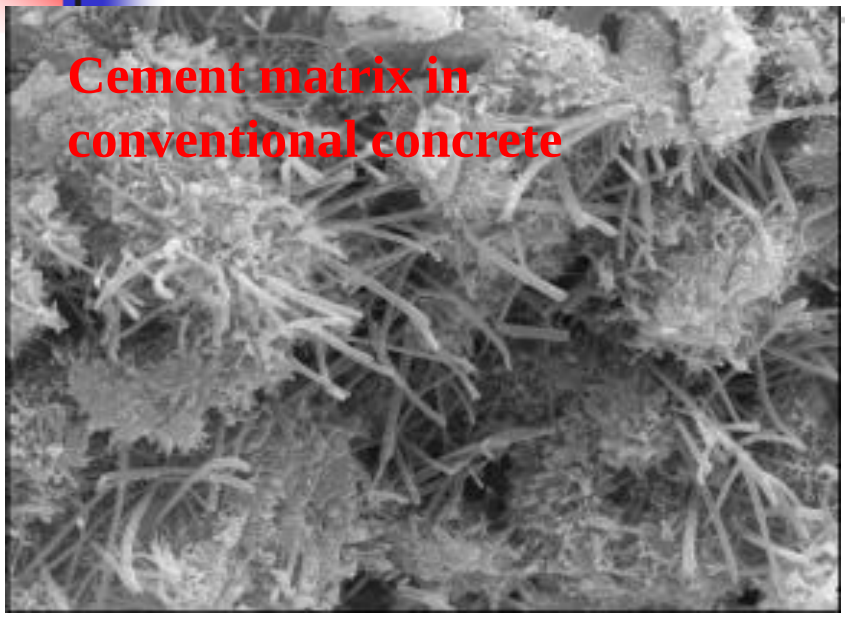


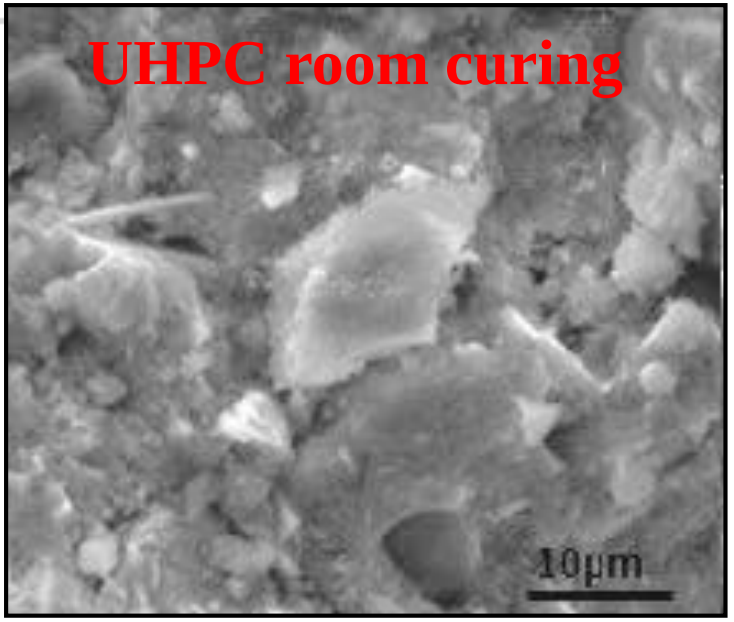


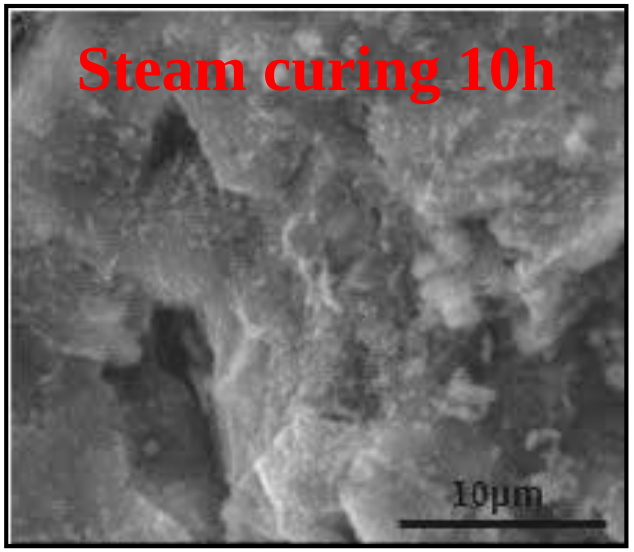


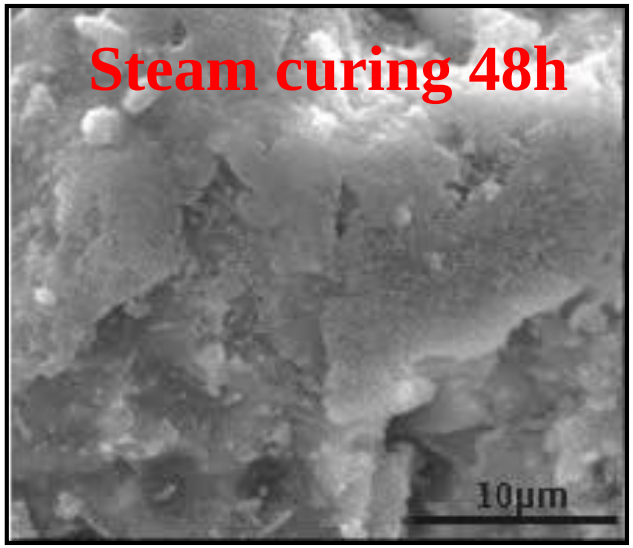


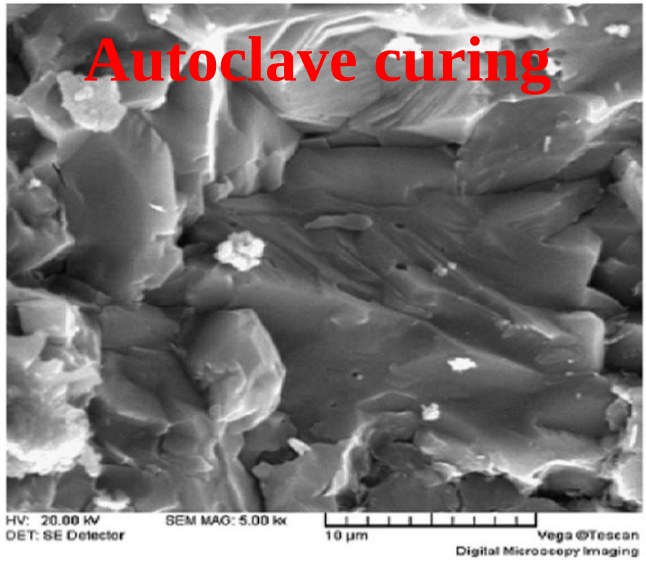
Principles for UHPC-Improvement in microstructure



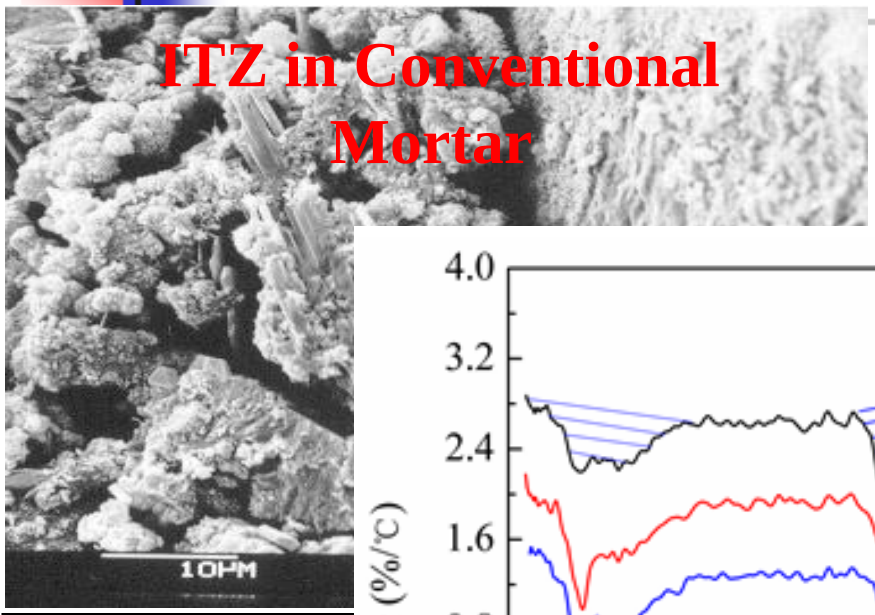


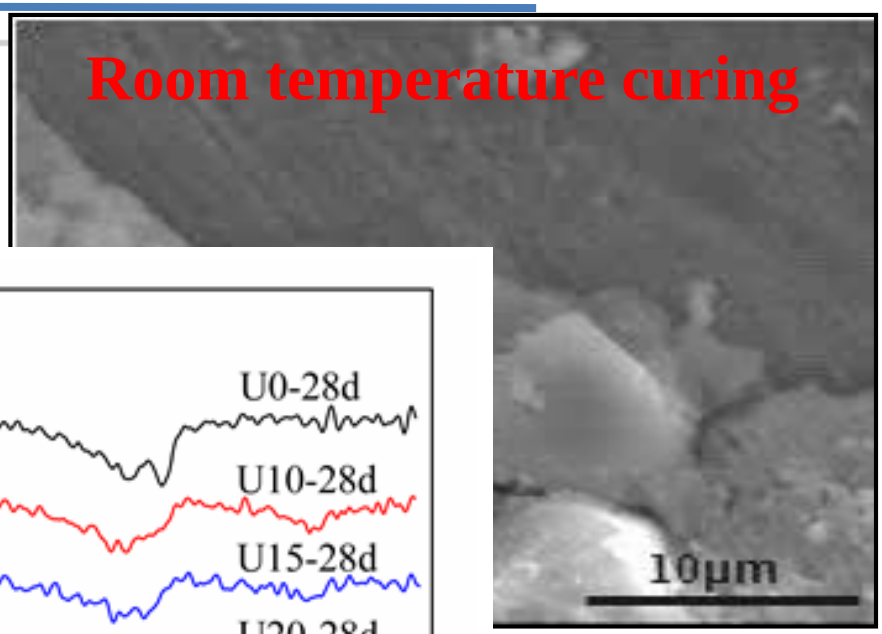


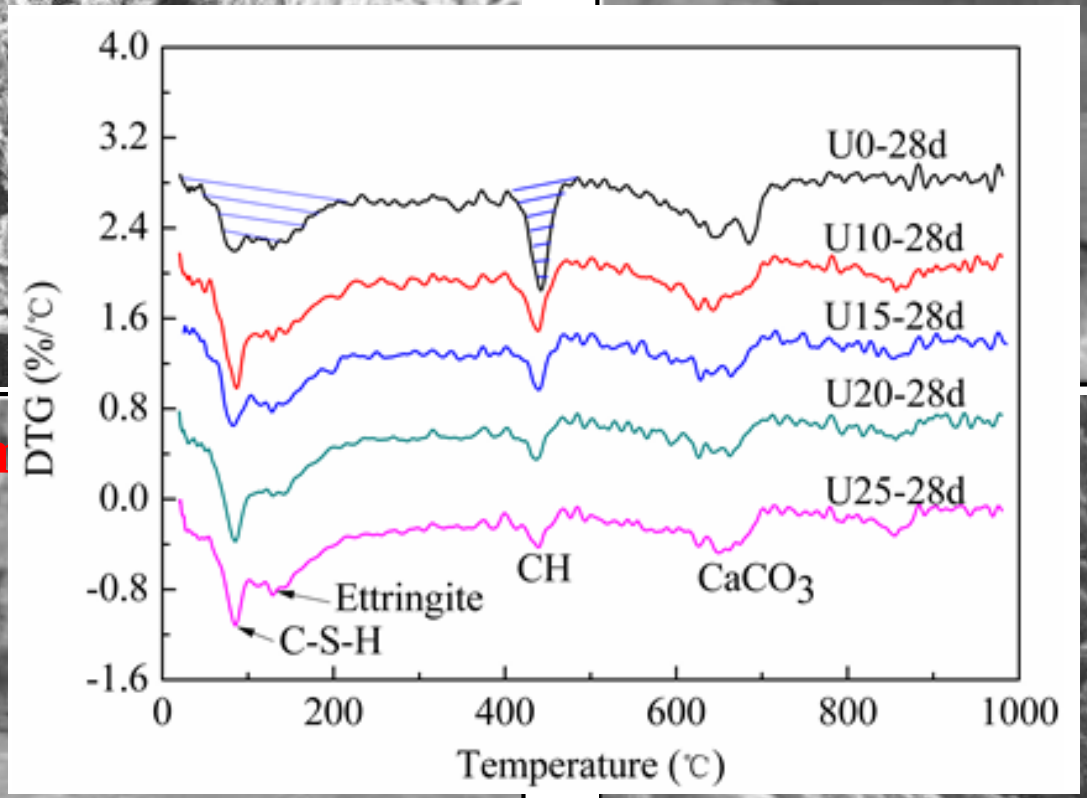


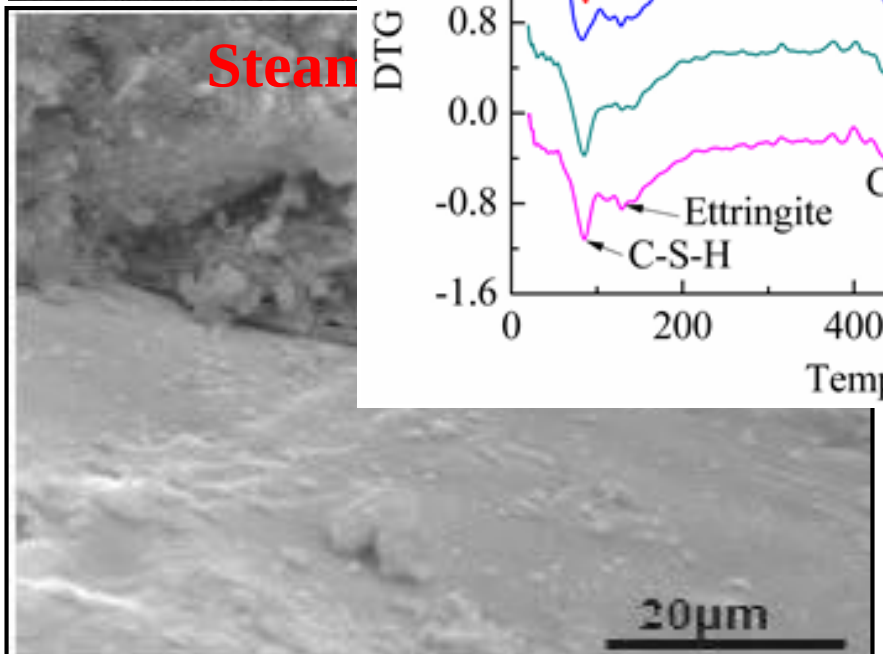


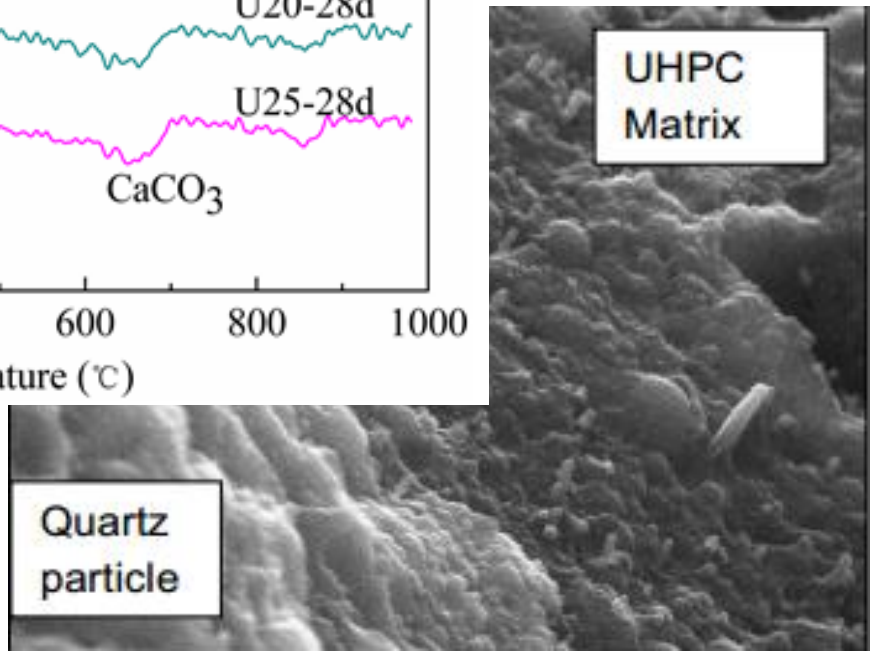
Principles for UHPC-Improvement in microstructure



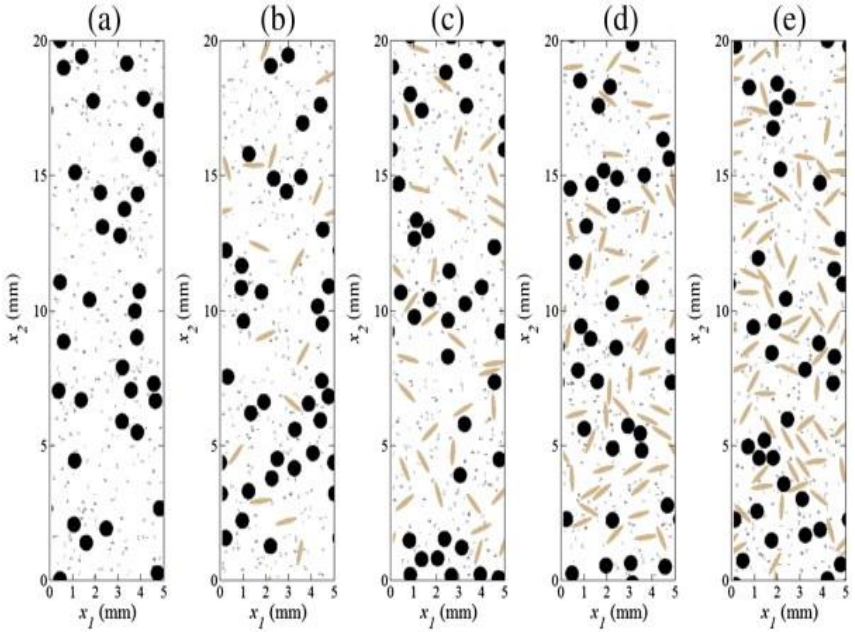


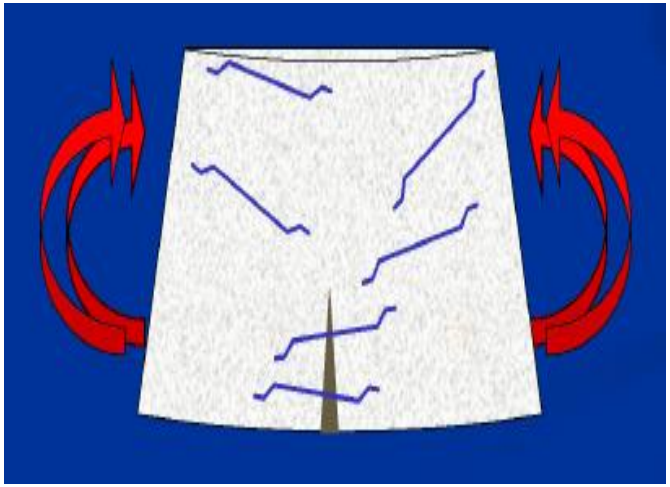


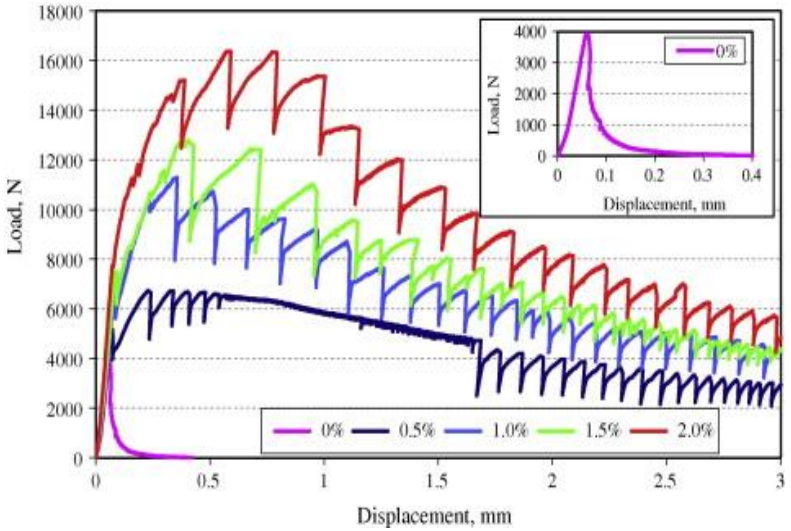




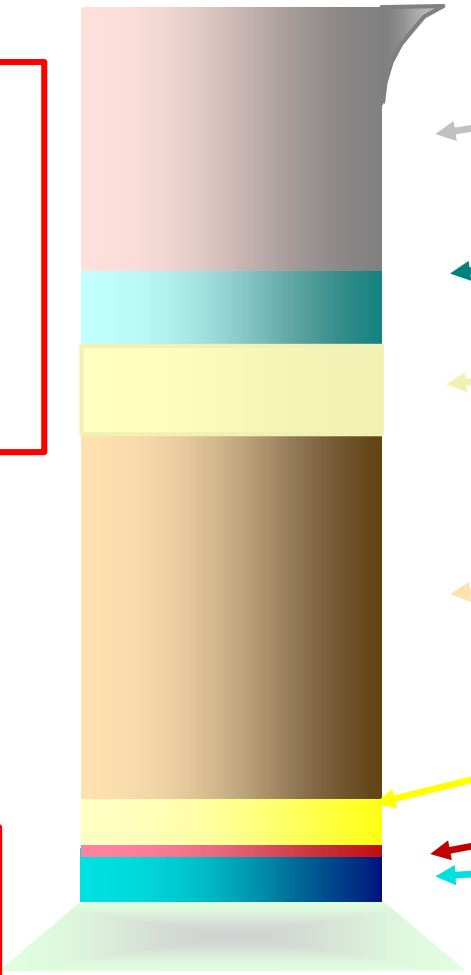
Principles for UHPC - Increase in toughness





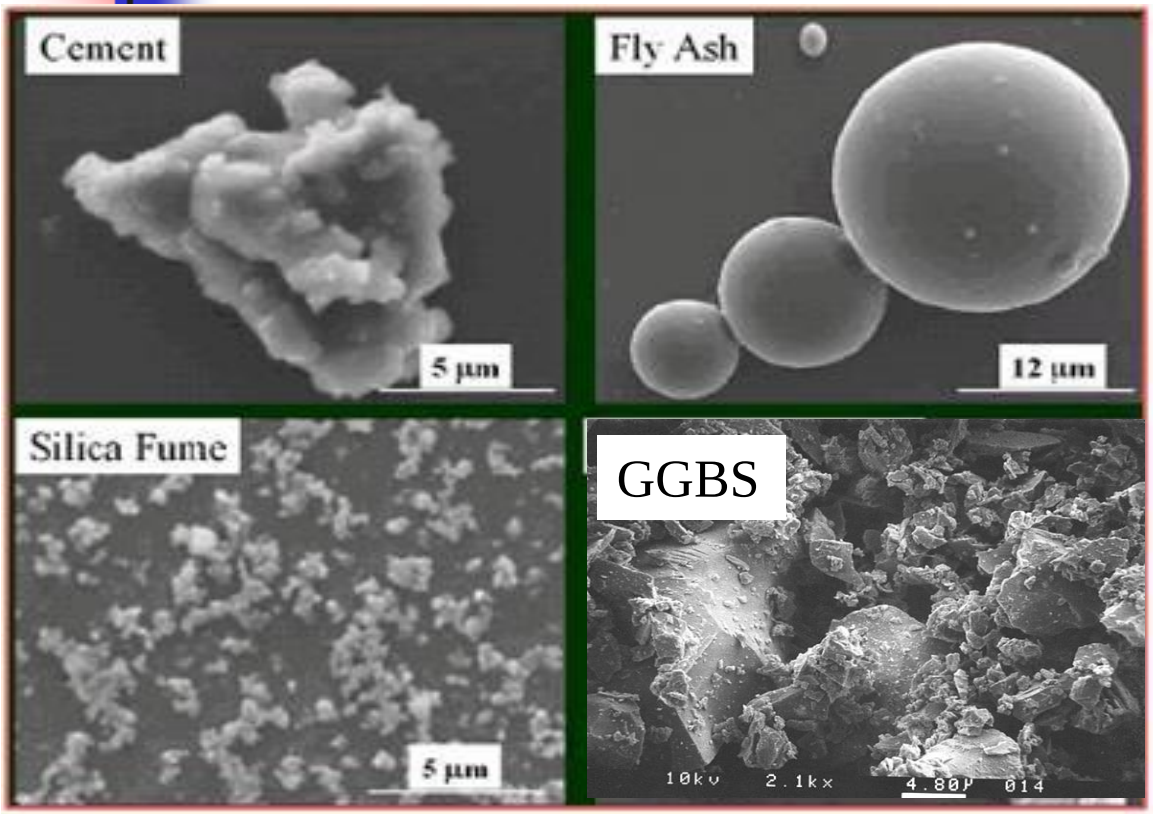


Typical UHPC mixture proportion

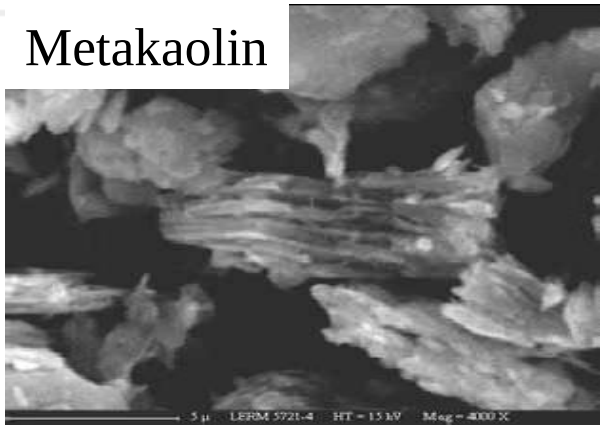


710 kg/m^3	Cement
	Silica fume
230 kg/m^3	
210 kg/m^3	quartz powder
1020 kg/m^3	Sand
	Fiber
40-160 kg/m^3	Superplasticizer
13 kg/m^3	
140 kg/m^3	Water

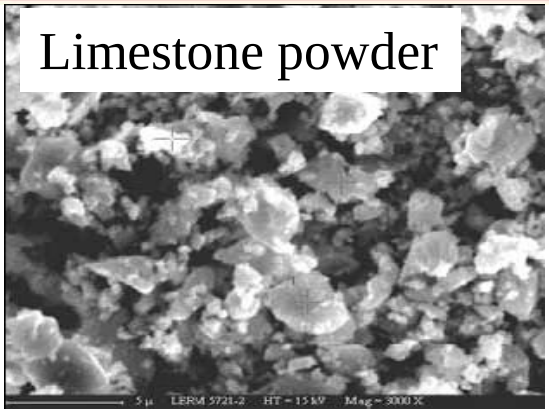
Cementing Components for UHPC



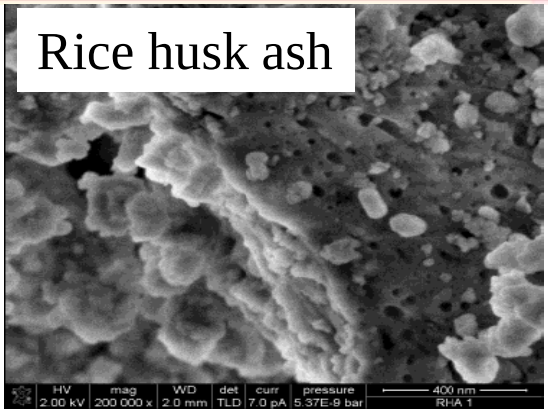
Metakaolin

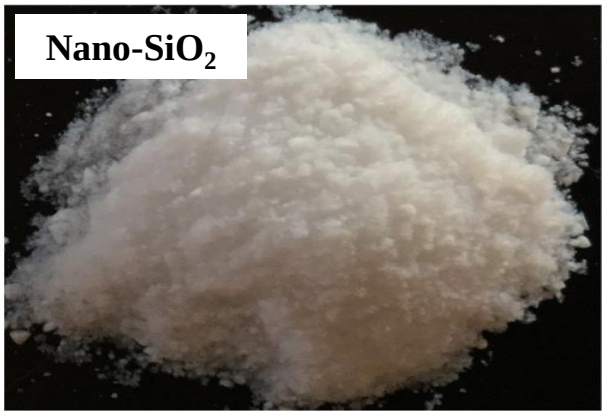


Limestone powder

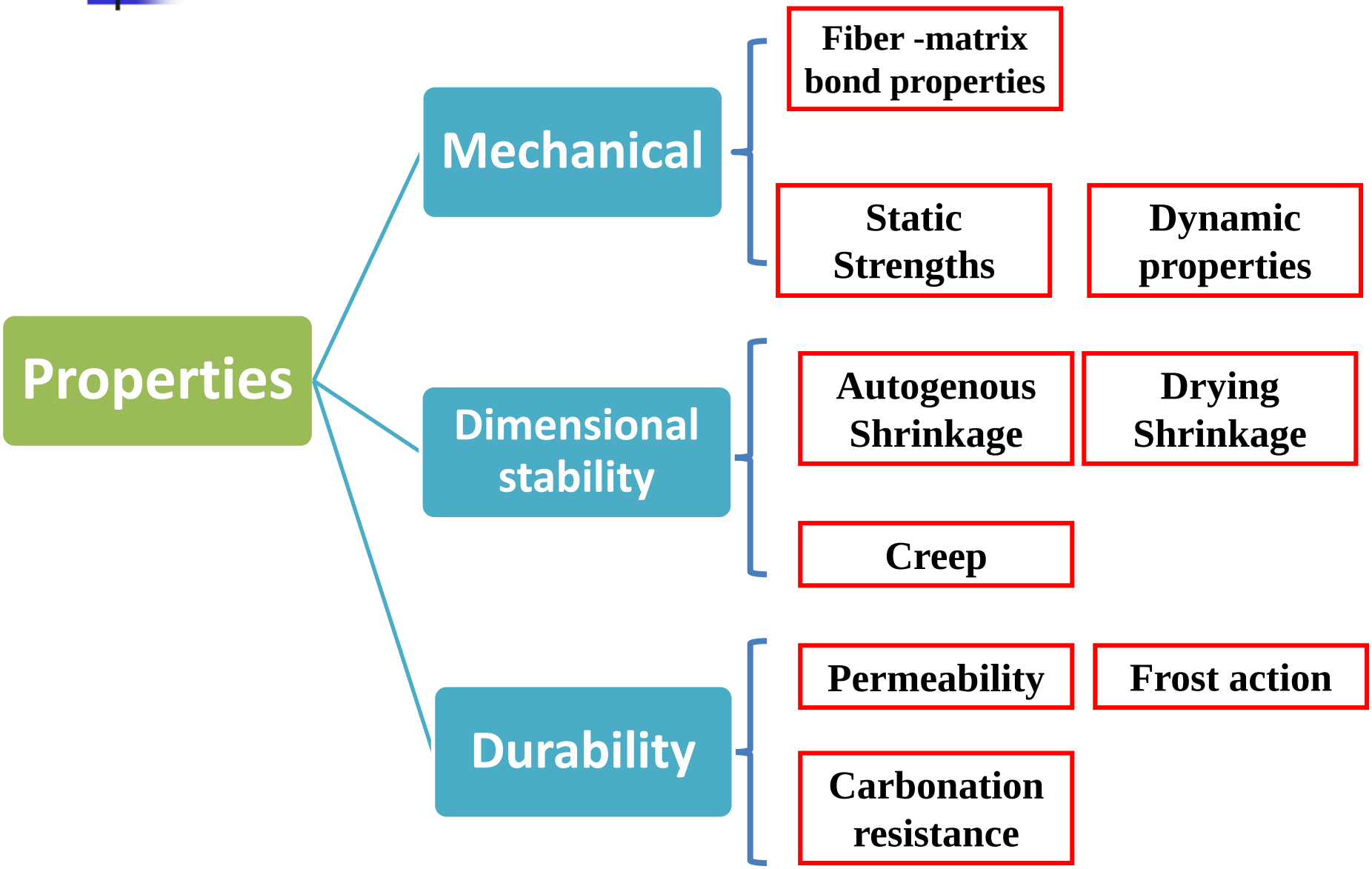


Rice husk ash

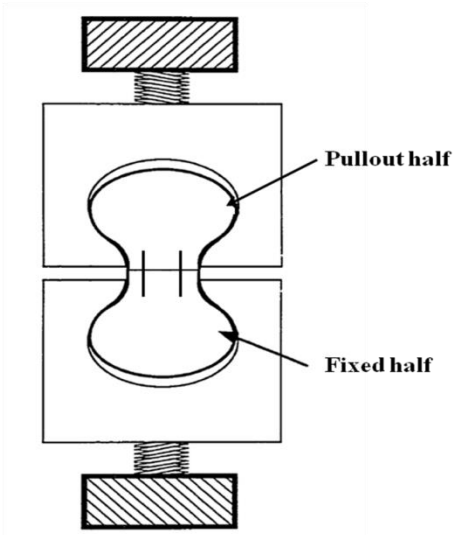


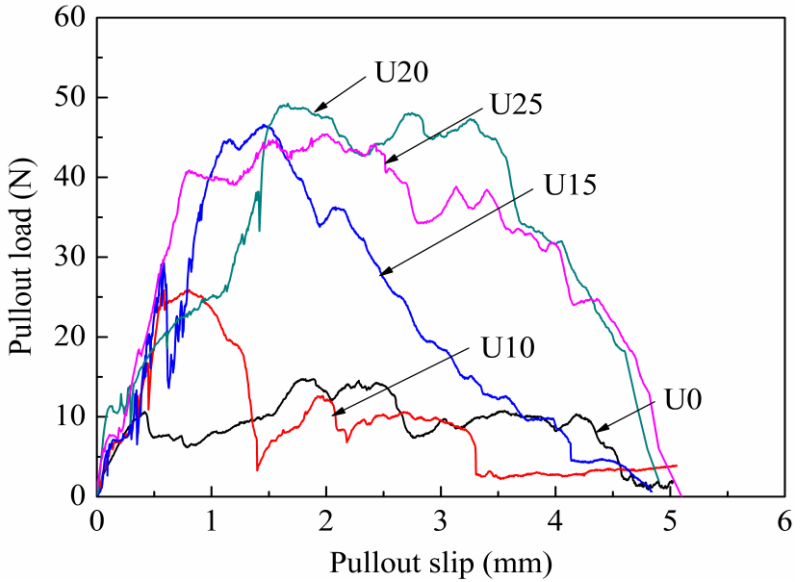


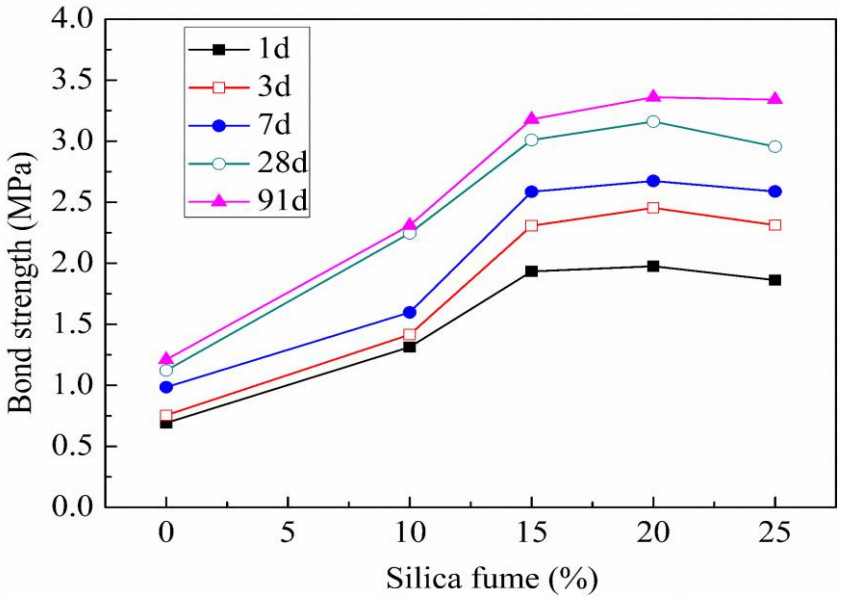
Properties of UHPC



Fiber-matrix bond properties



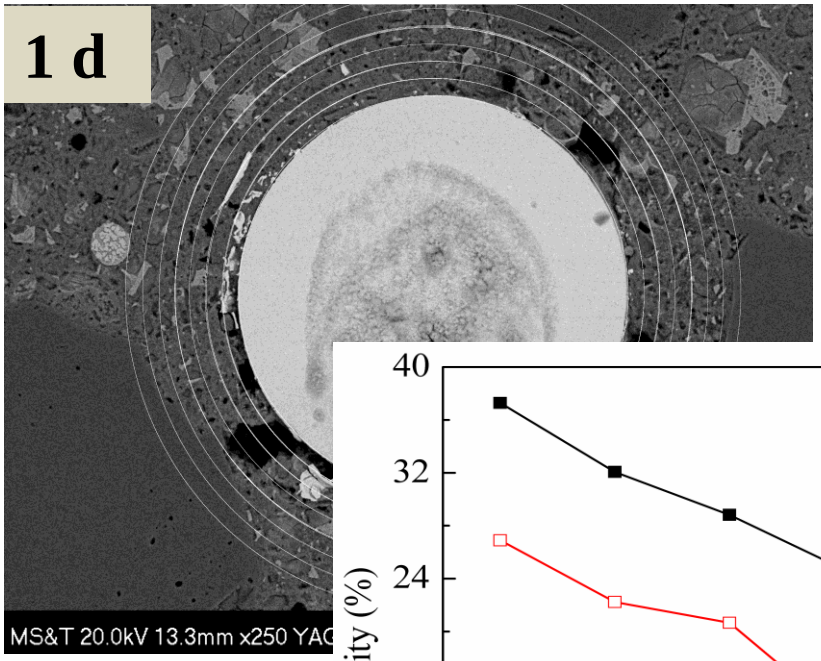


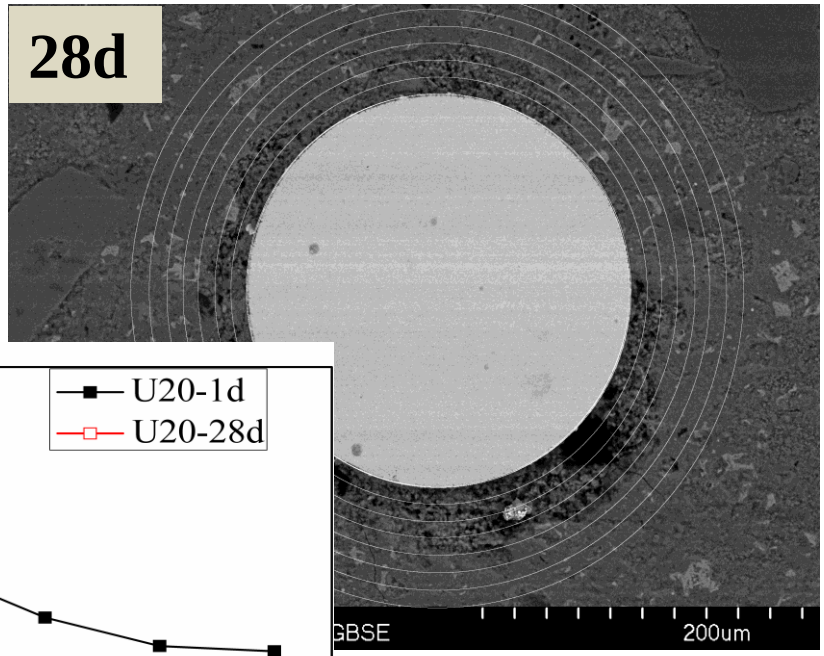


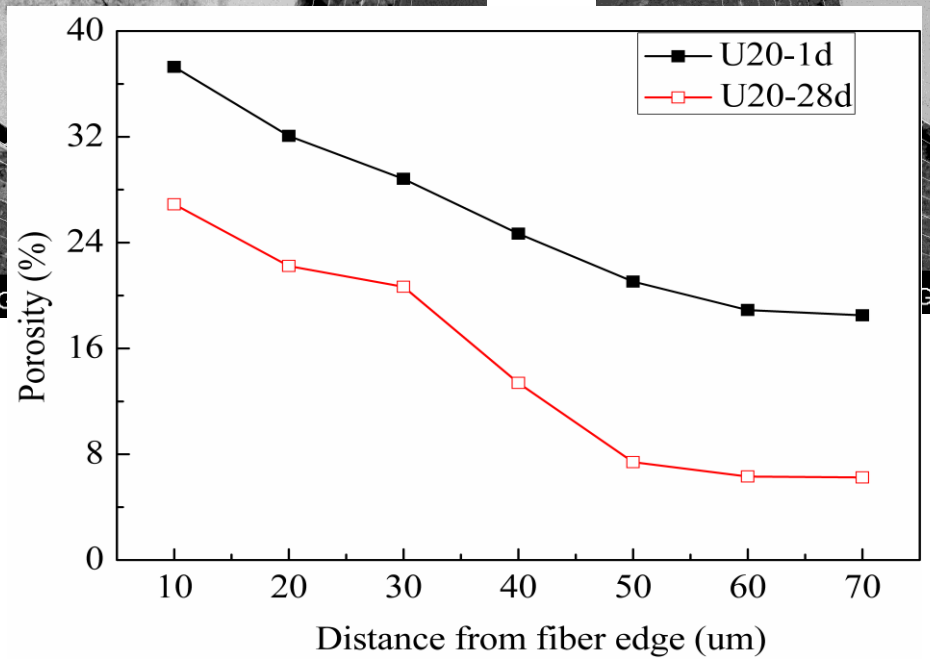
- Samples with 15-25% silica fume had the optimal bond properties
- Maximum bond strength of 3.5 MPa can be obtained under normal room temperature curing.

ITZ Microstructure Development

BSEM images of U20 samples with an embedded fiber

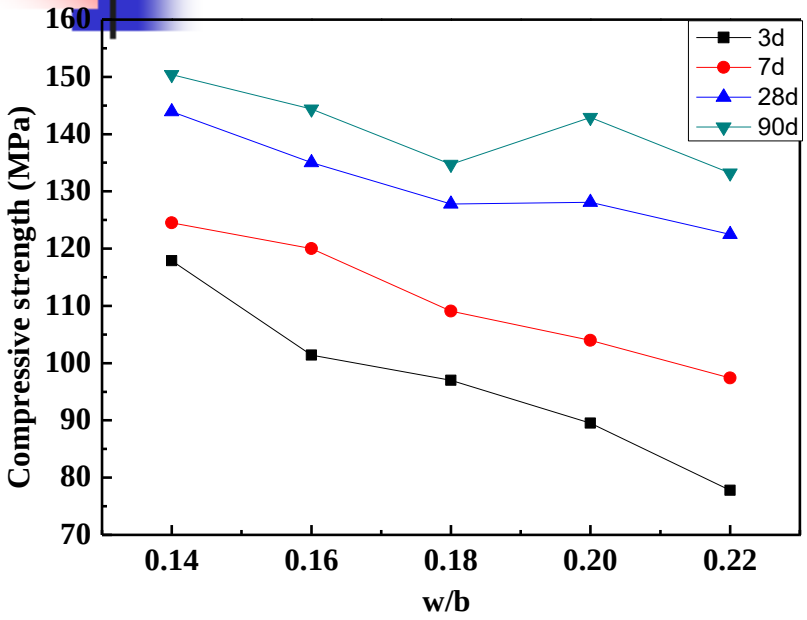


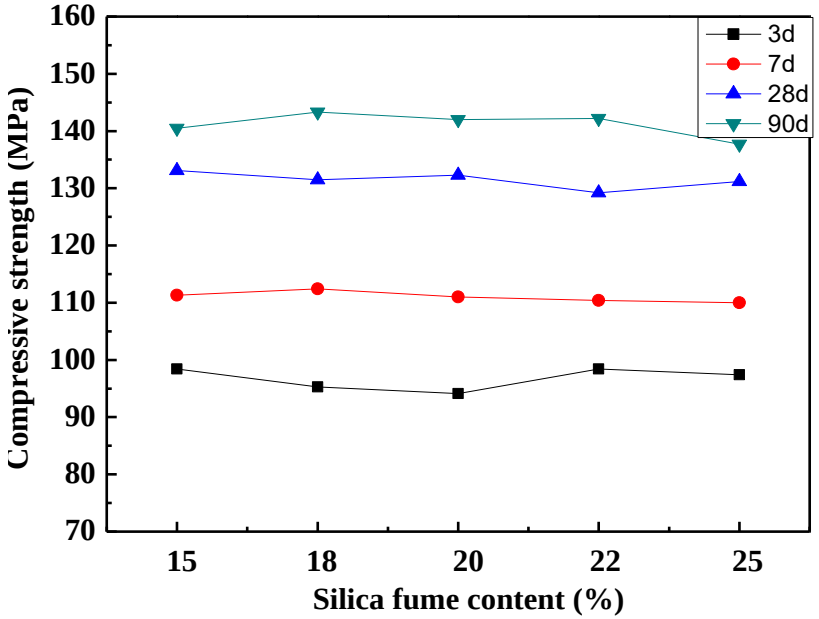


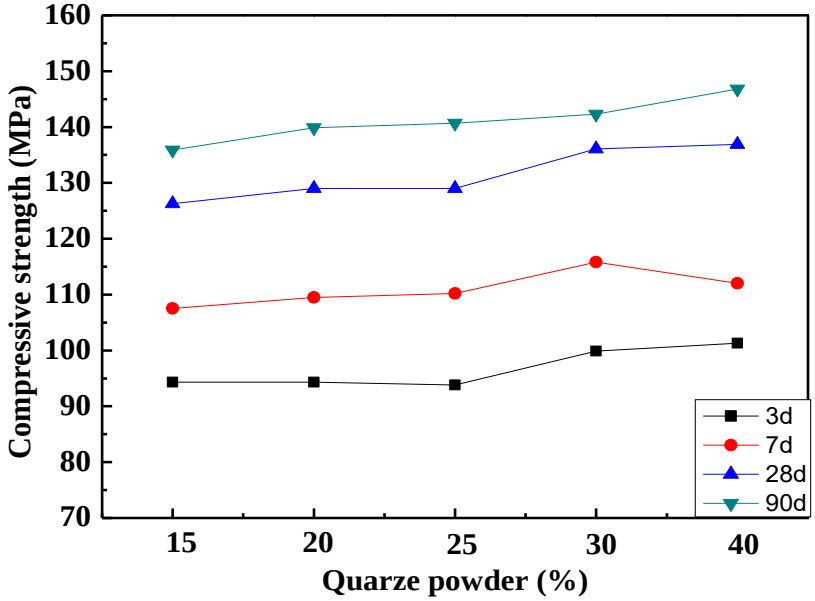


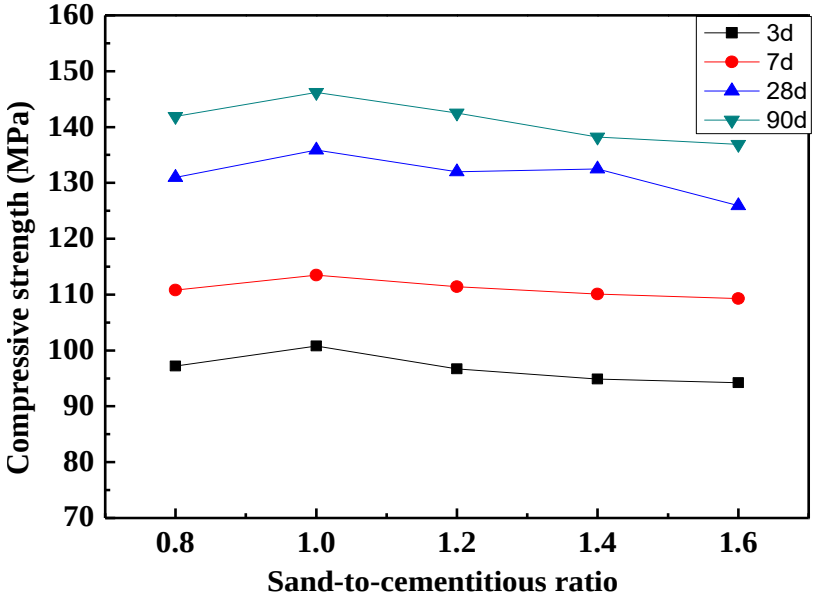
Z. Wu, C. Shi, K. Khayat, Influence of silica fume content on microstructure development and bond to steel fiber in ultra-high strength cement-based materials (UHSC), Cem. Concr. Compos. 71 (2016) 97-109.

Compressive strength

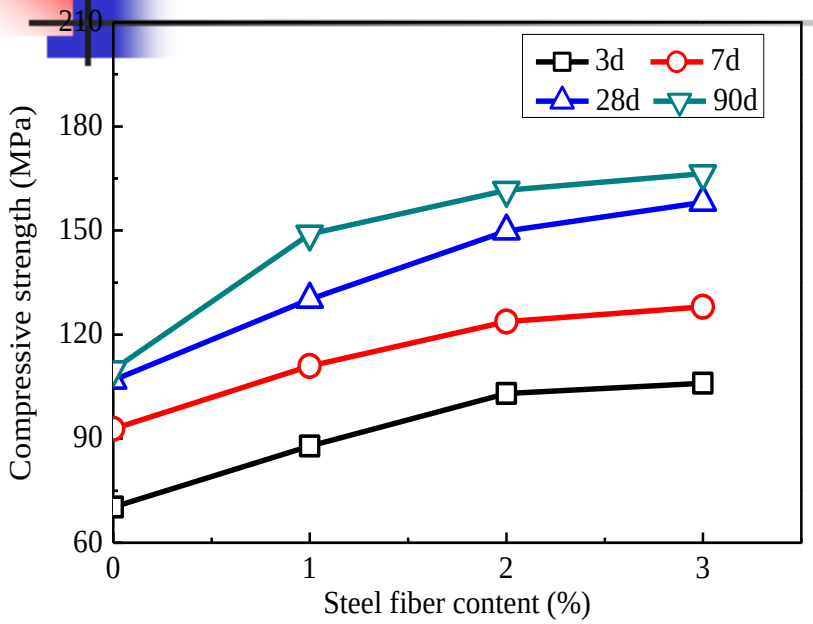


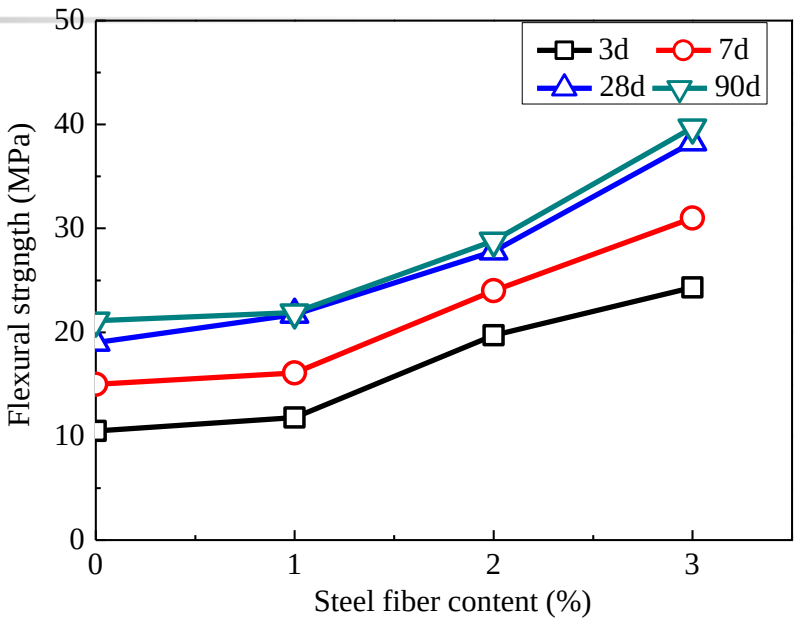


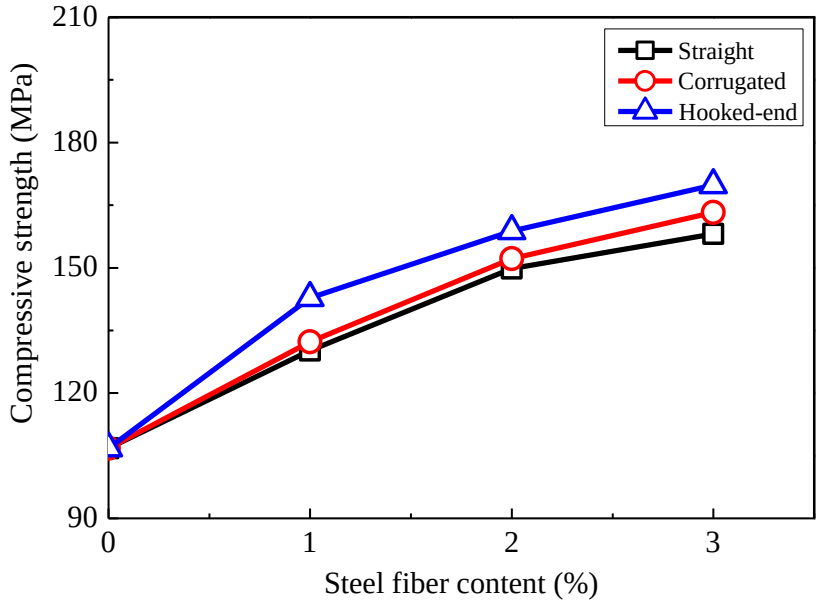


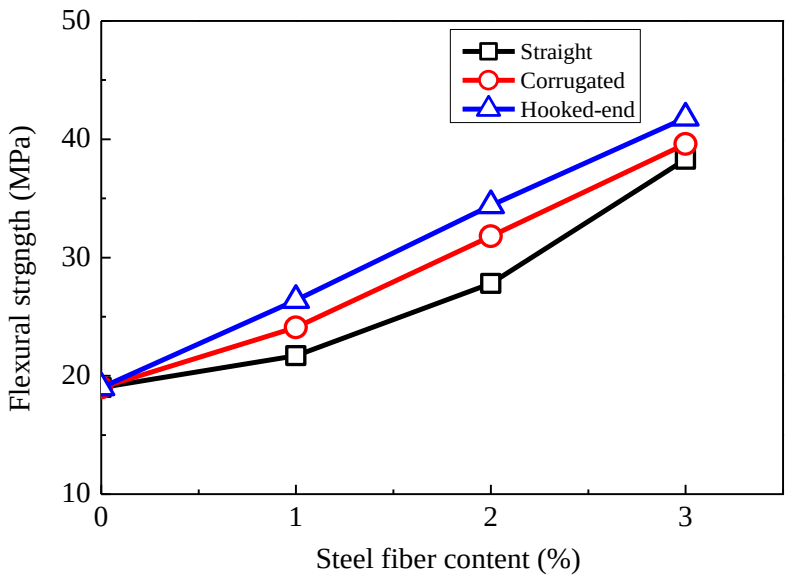


Compressive strength- fiber content and shape

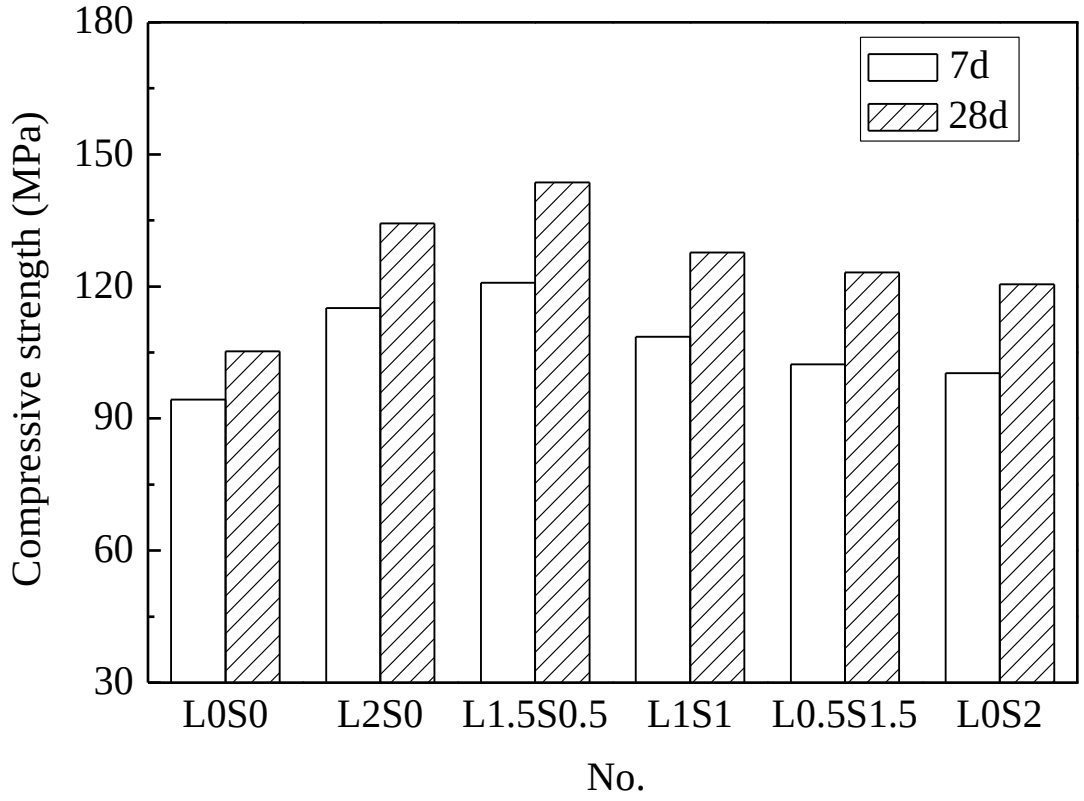




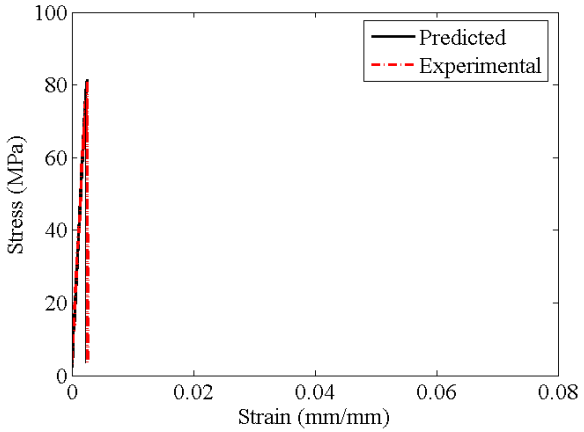




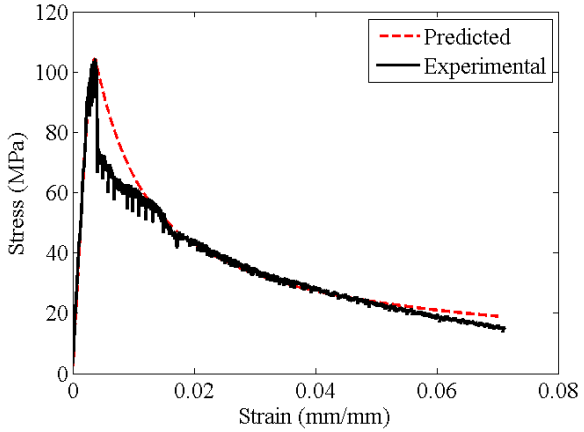
Compressive strength- hybrid steel fiber



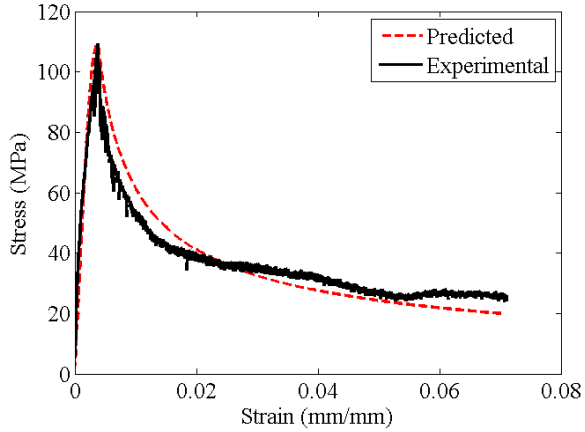
Stress-Strain Relationship



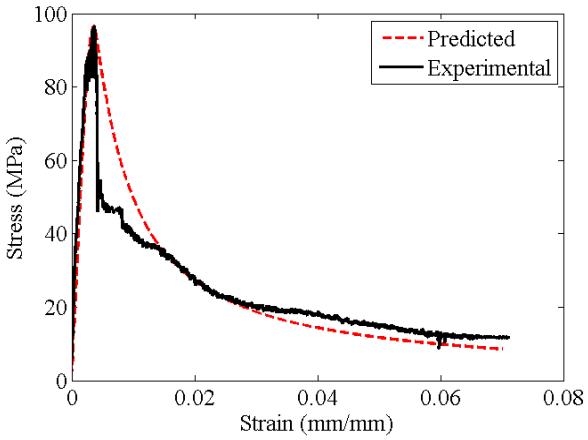
(a) L0S0



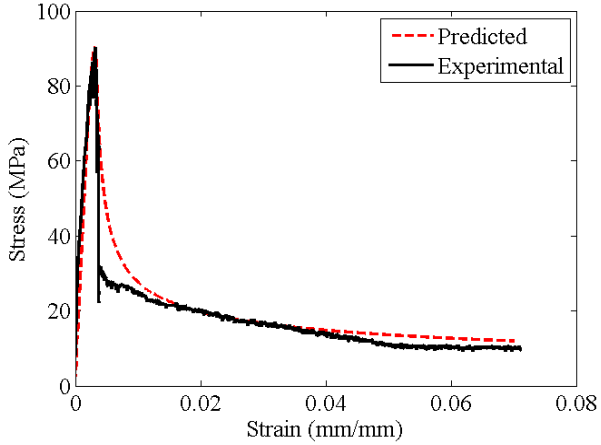
(b) L2S0



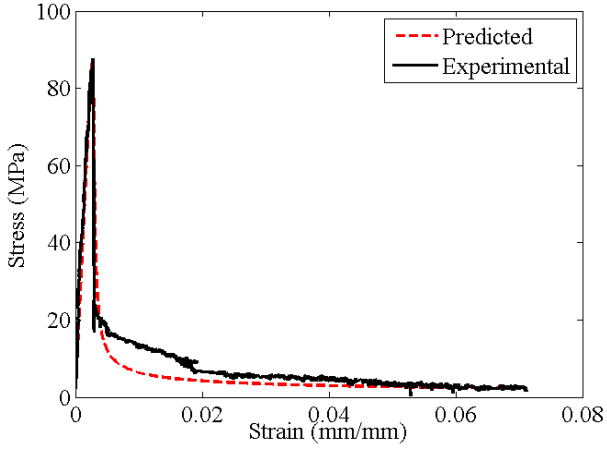
(c) L1.5S0.5



(d) L1S1

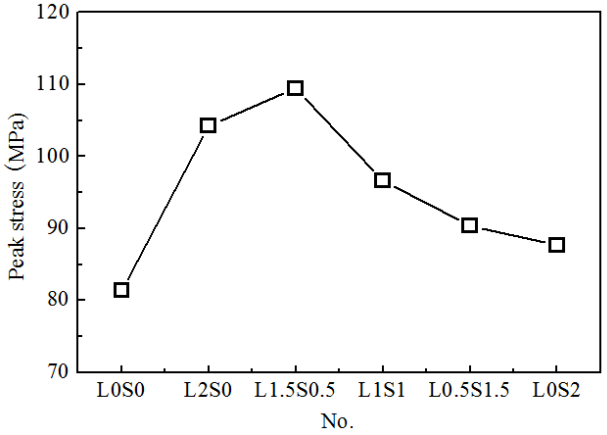


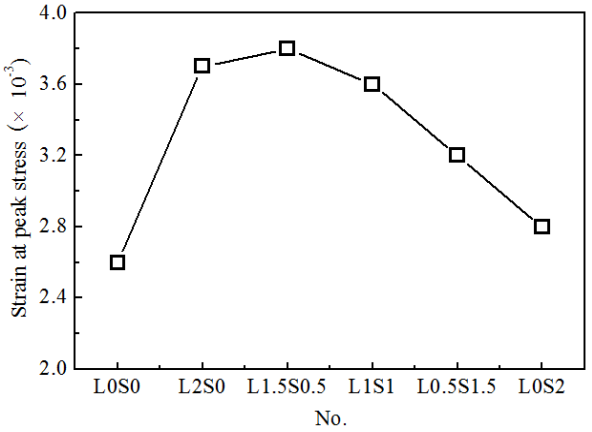
(e) L0.5S1.5

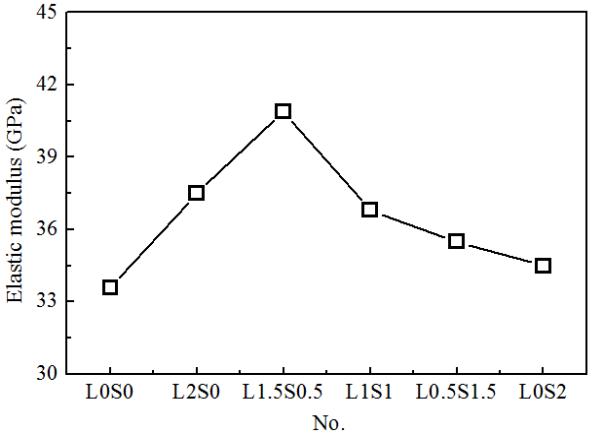


(f) L0S2

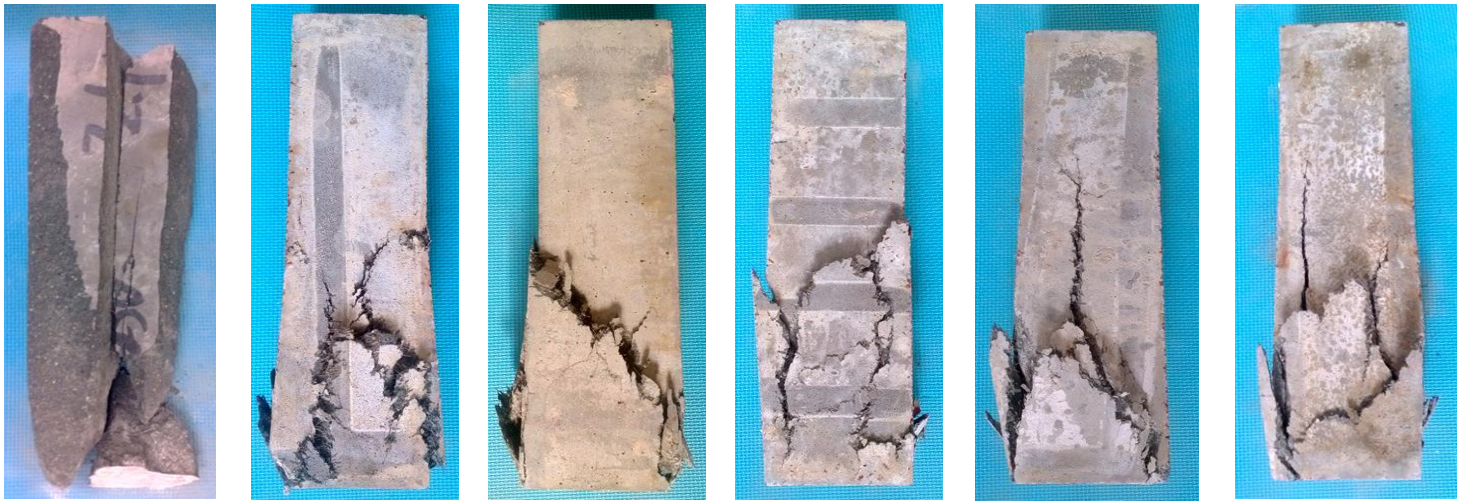
Mechanical Properties of UHPC







破坏形态



L0S0 L2S0 L1.5S0.5 L1S1 L0.5S1.5 L0S2

➢**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：

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

Downside：

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

其中：

$$\beta = \frac{1}{1 - \frac{f_0}{\varepsilon_0 E}}$$

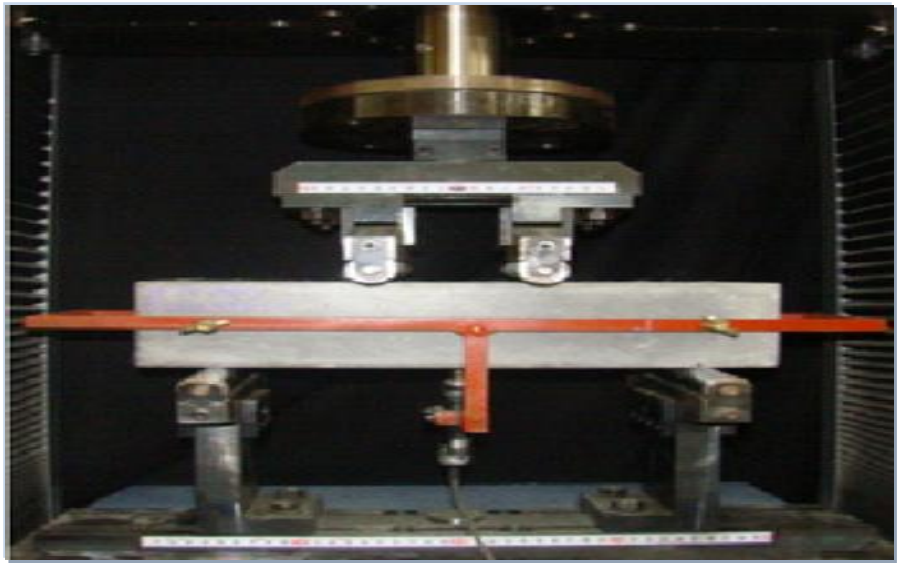
Different Relationships of UHPC with Hybrid Fiber：

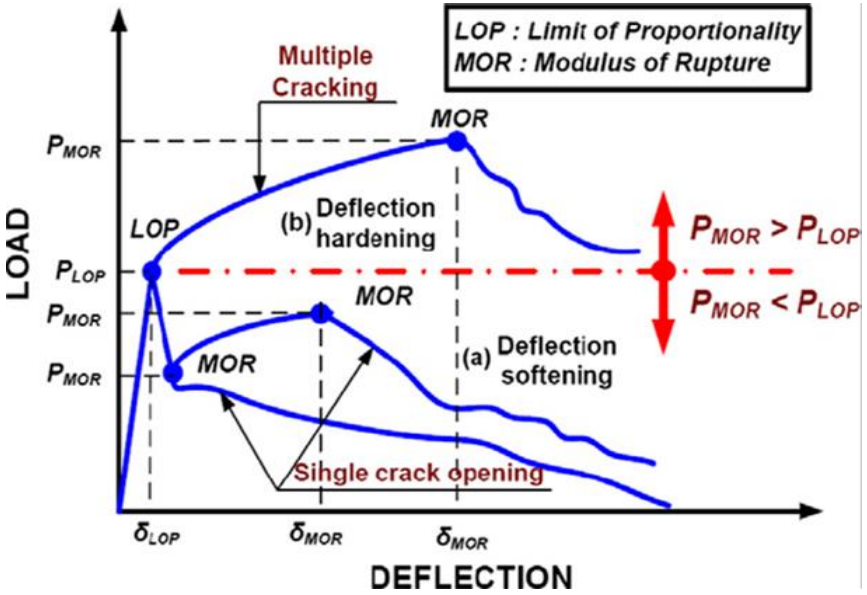
Peak stress = 99.014 + 12.713V_l + 2.273V_s -2.629V_l^2 **R^2 = 0.90** **(1)**

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

Elastic modulus = 37.897 + 2.431 V_l + 0.151 V_s -1.714 V_l^2 **R^2 = 0.75** **(3)**

Bending strength and toughness





Evaluation methods of toughness

- **ASTM C1018** ⇒ η_5 , η_{10}, η_{20}

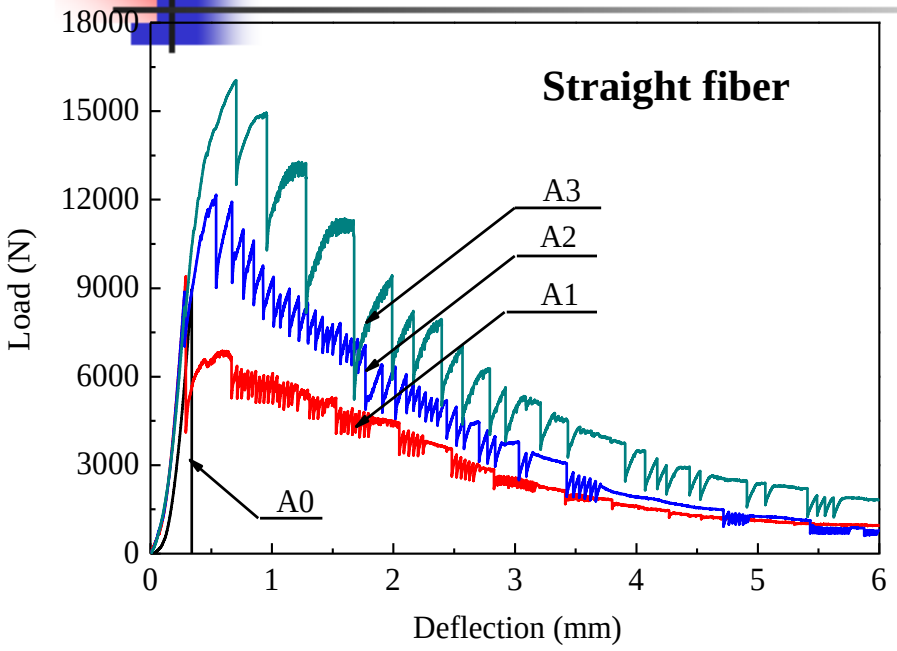
  The η_5, η_{10}, and η_{20} are the values by dividing the area up to a deflection of 3, 5.5, and 10.5 times of the first crack deflection by the area up to first crack.

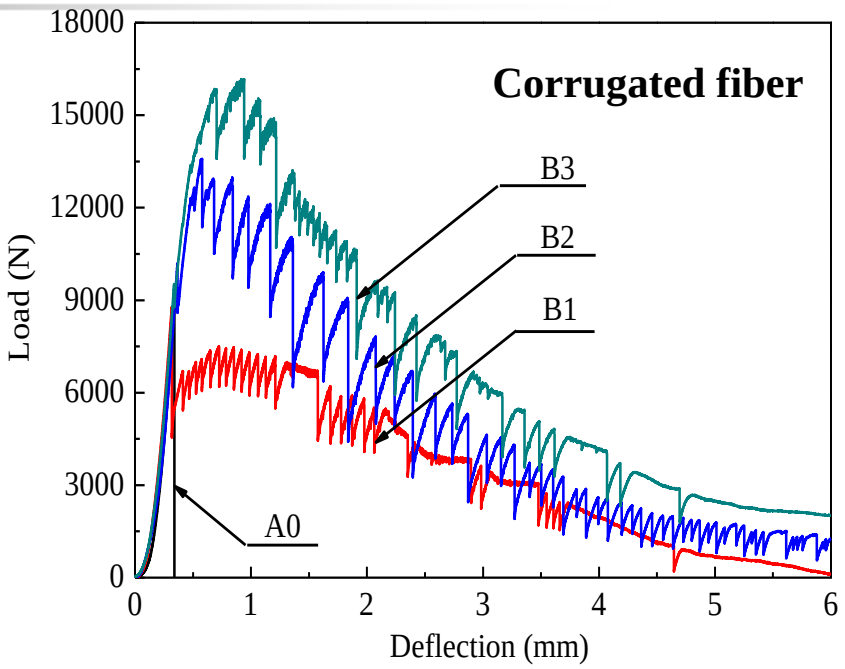
- **JSCE SF4**

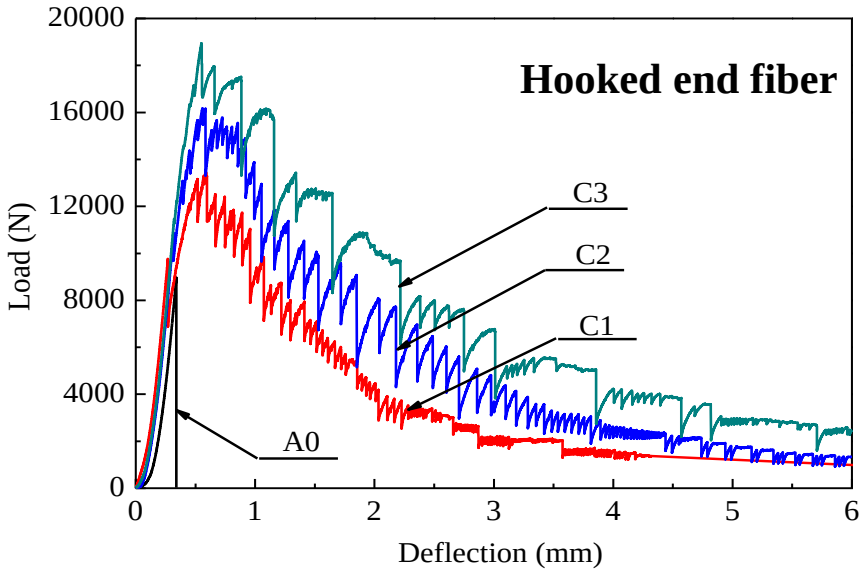
- **RILEM TC 162-TDF**

$$I_G = \frac{G_{0.8}}{G_m}$$

Bending properties-fiber content and shape

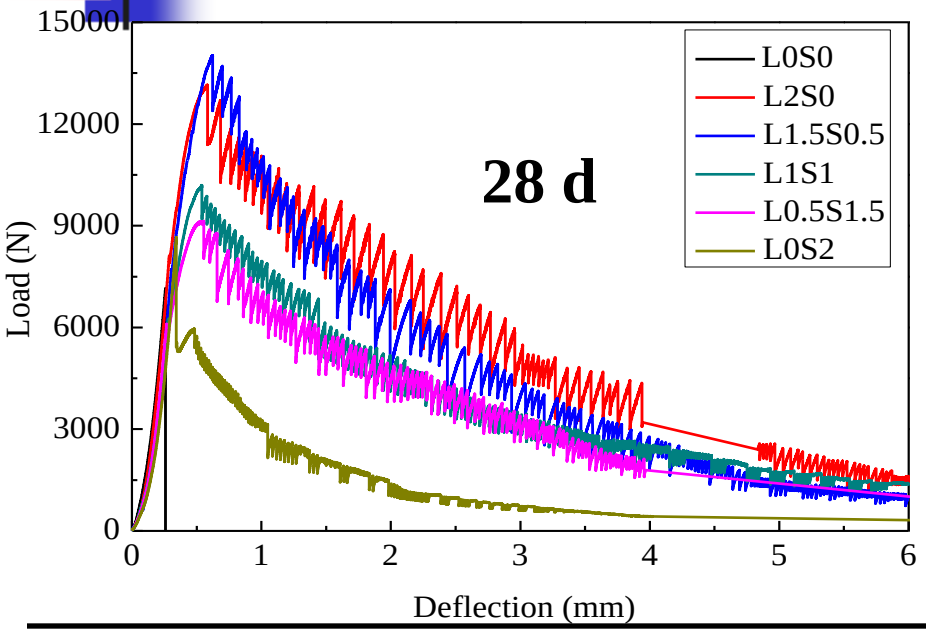


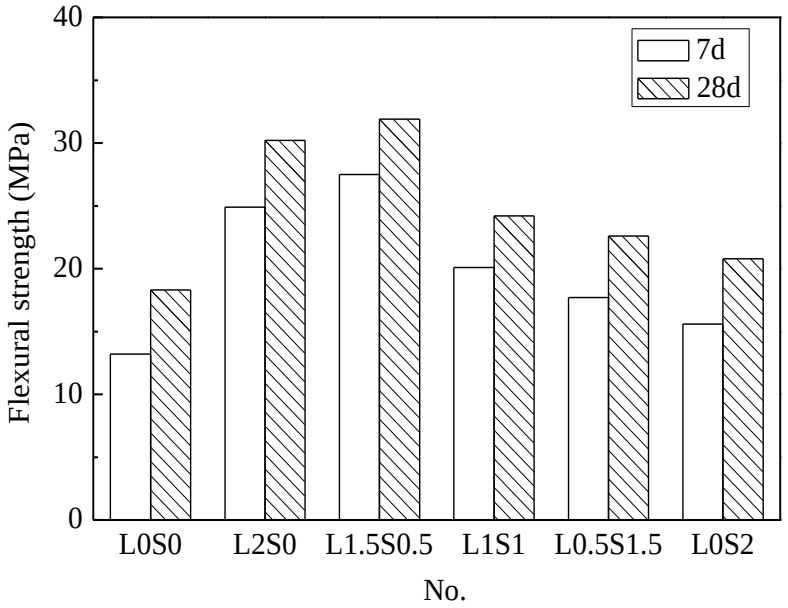




No.	First crack strength (MPa)	First crack deflection (mm)	Peak strength (MPa)	Peak deflection (mm)	Toughness indexes		
					η5	η10	η20
A0	19.0	0.30	19.0	0.30	1.00	1.00	1.00
A1	19.2	0.31	21.7	0.36	4.79	9.08	14.56
A2	19.3	0.32	27.8	0.53	7.86	14.95	22.05
A3	19.9	0.33	38.3	0.80	10.17	19.78	27.10

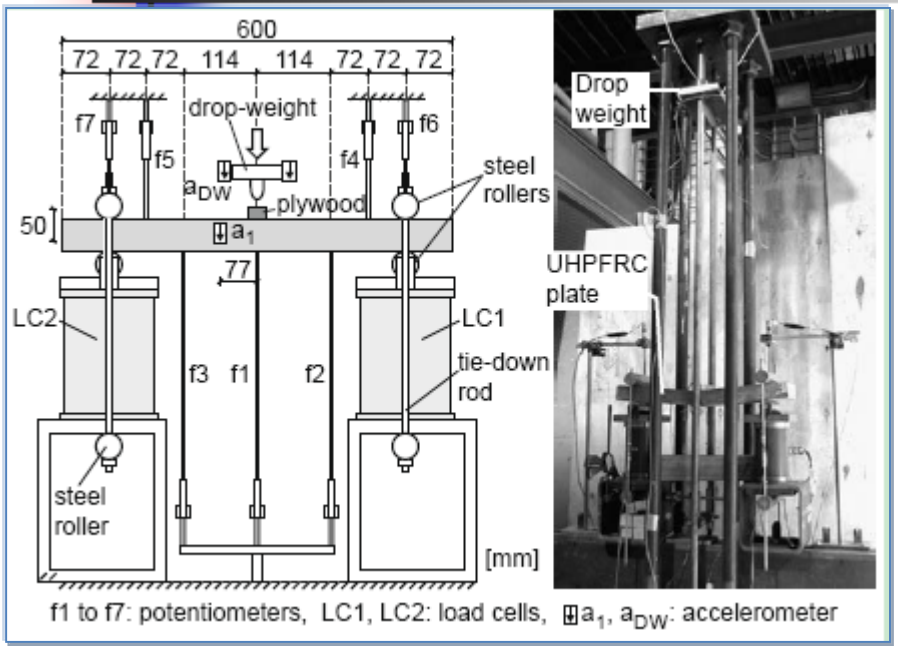
Bending properties-hybrid steel fiber





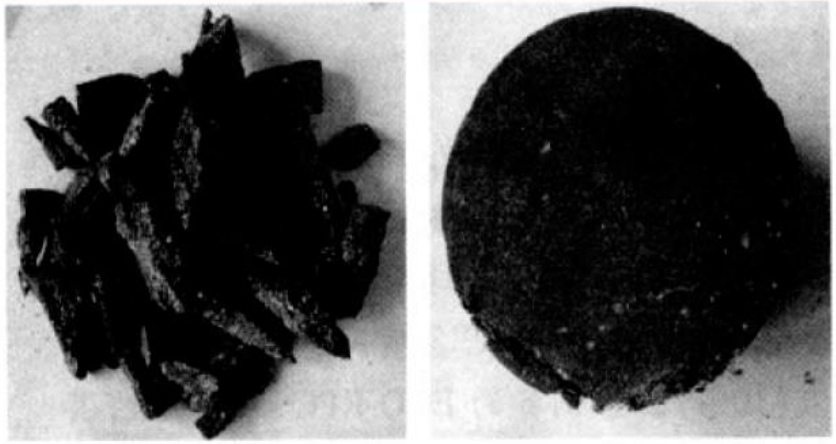
No.	Pre-cracking strength (MPa)	Pre-cracking deflection (mm)	Peak strength (MPa)	Deflection at peak stress (mm)	Toughness index		
					η_5	η_{10}	η_{20}
L0S0	18.3	0.26	18.3	0.26	1.00	1.00	1.00
L2S0	19.1	0.31	30.2	0.54	8.54	15.33	23.06
L1.5S0.5	19.0	0.30	31.9	0.53	8.63	14.77	21.29
L1S1	18.7	0.28	24.2	0.49	6.85	12.82	19.25
L0.5S1.5	18.5	0.27	22.6	0.47	6.53	12.21	18.59
L0S2	18.4	0.26	20.8	0.36	5.39	10.45	15.60

Dynamic properties-Impact properties



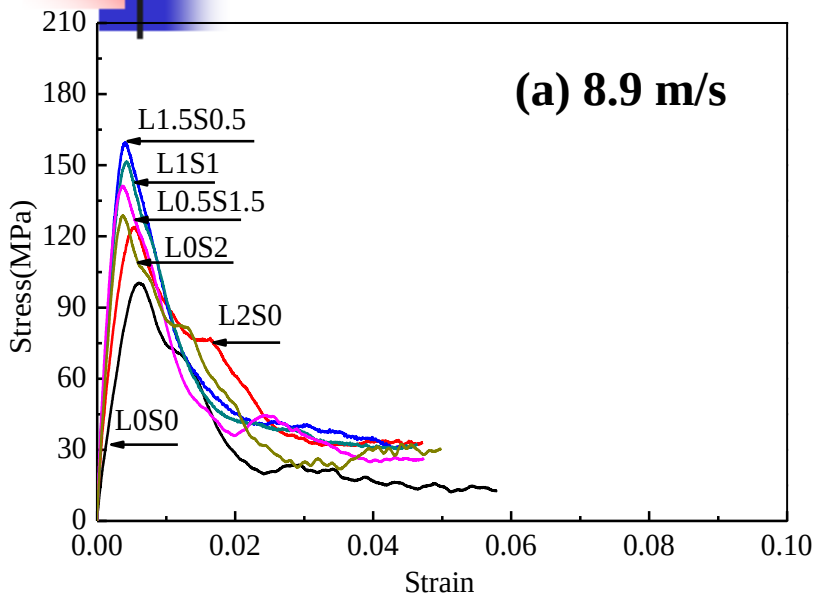
drop weight testing

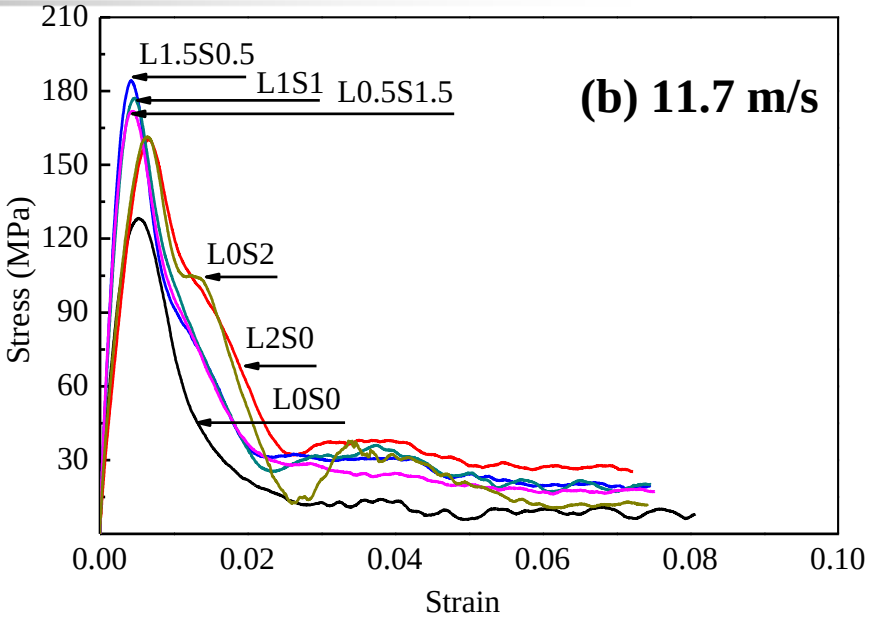
split hopkinson pressure bar (SHPB)

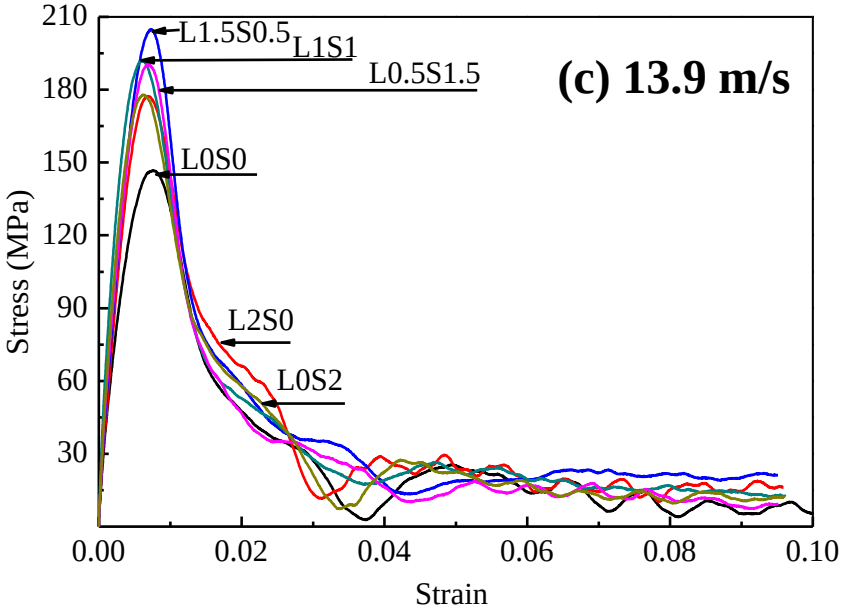


UHPFRC is sensitive to the strain rate. Under the same compressive loading, the sample of UHPFRC matrix was crushed while the sample made of UHPFRC with 3% or 4% of steel fibers by volume fraction remained essentially intact.

Dynamic properties-Impact properties

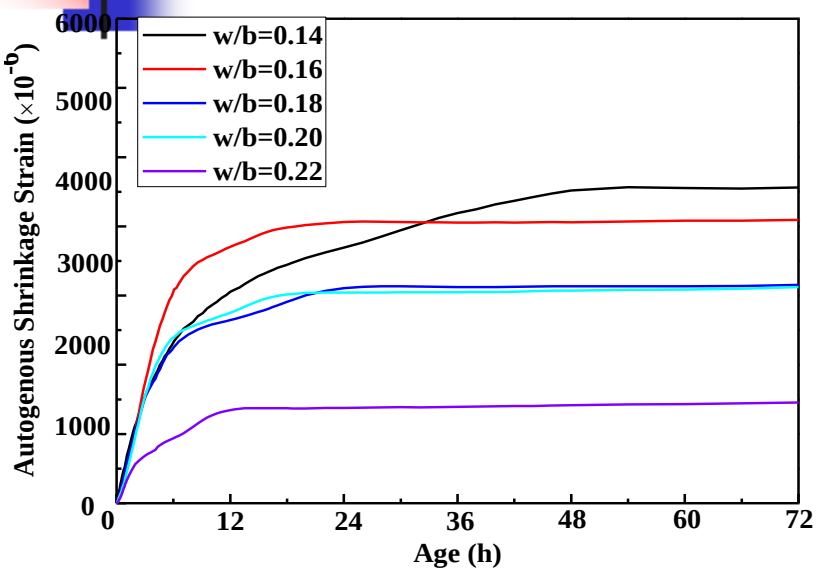




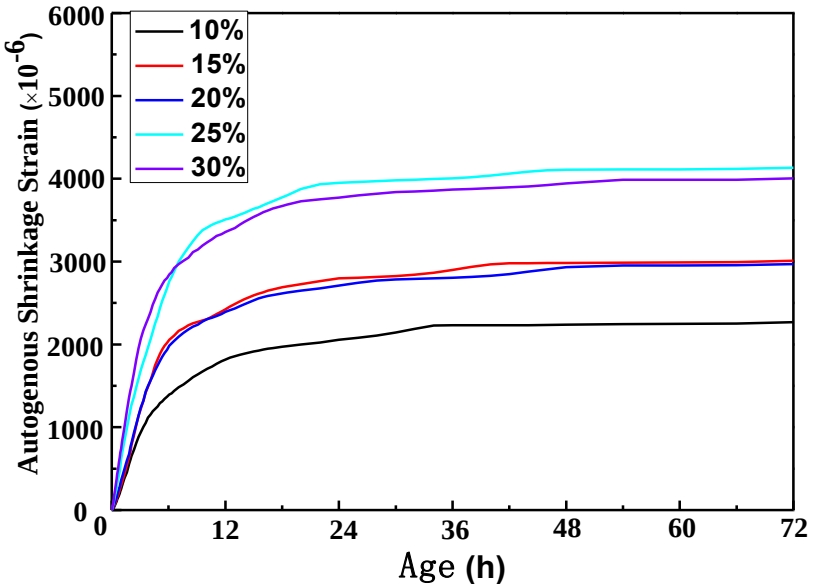


- **The peak stress increased with the increase of strain rate, showing strain rate effect**
- **L1.5S0.5 mixture had the highest dynamic properties, followed by L1S1 and L0.5S1.5 mixtures**
- **L2S0 showed comparable peak stress to L0S2**

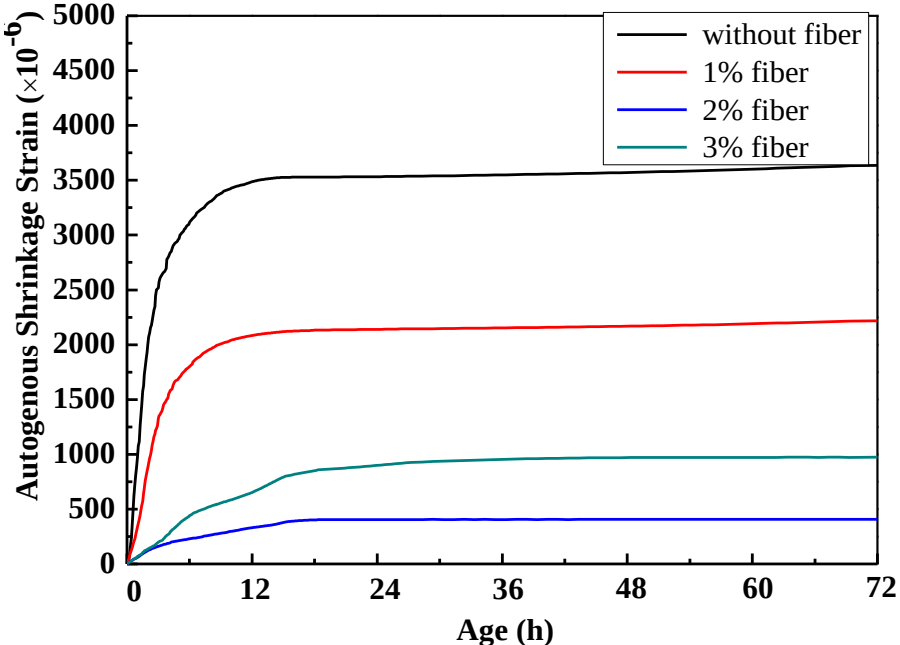
Autogenous shrinkage of UHPC



W/B



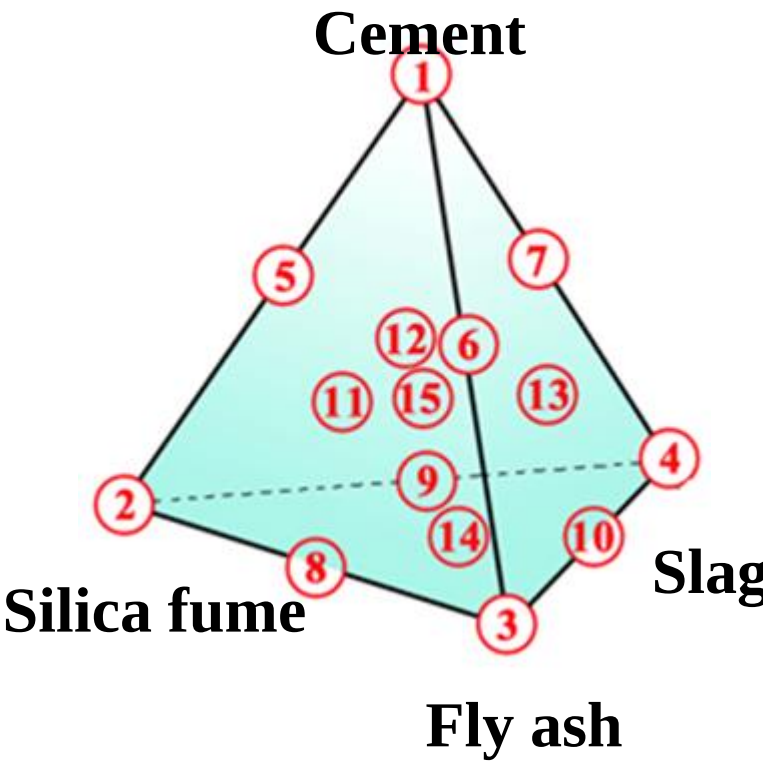
Silica fume content



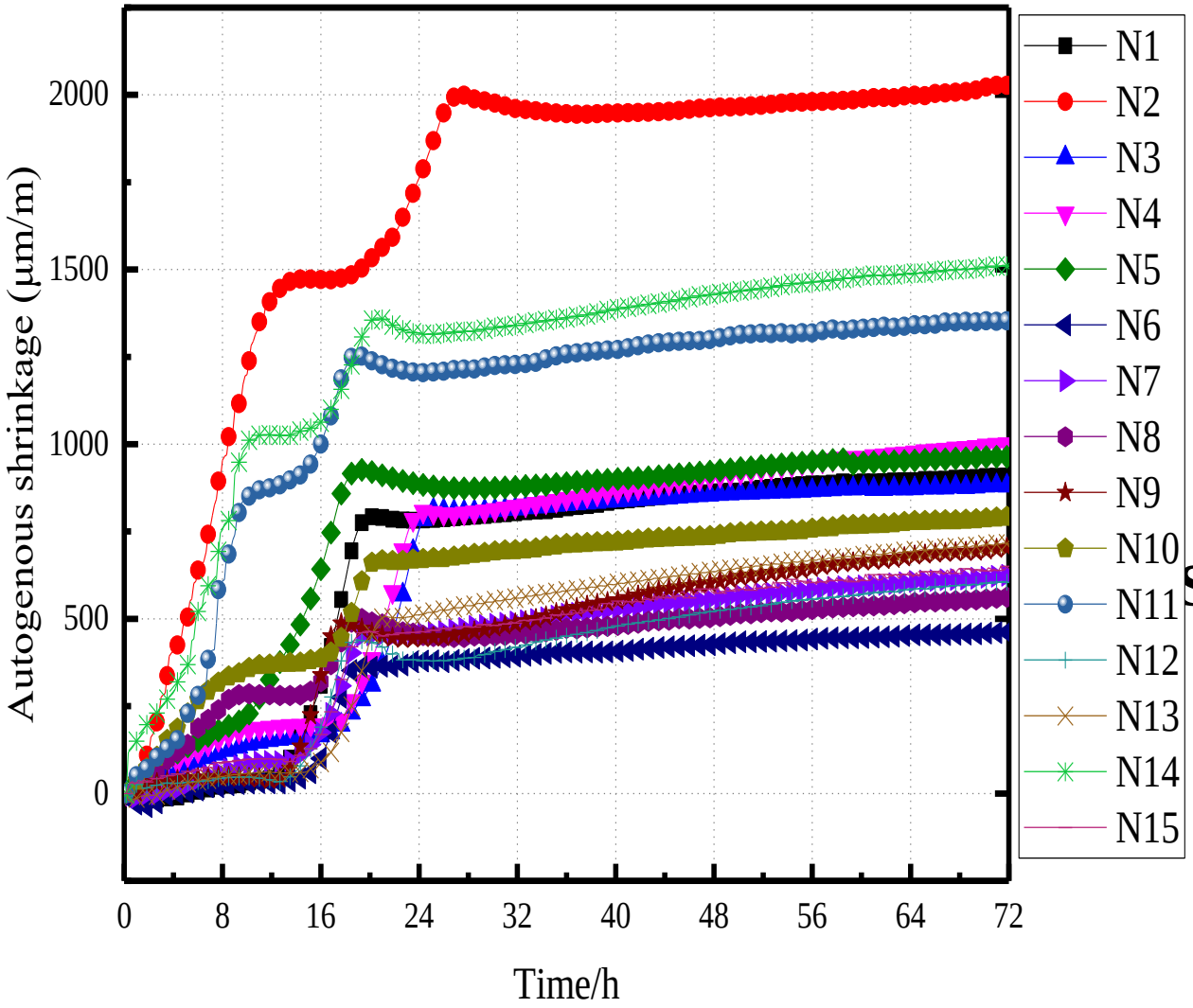
Fiber content

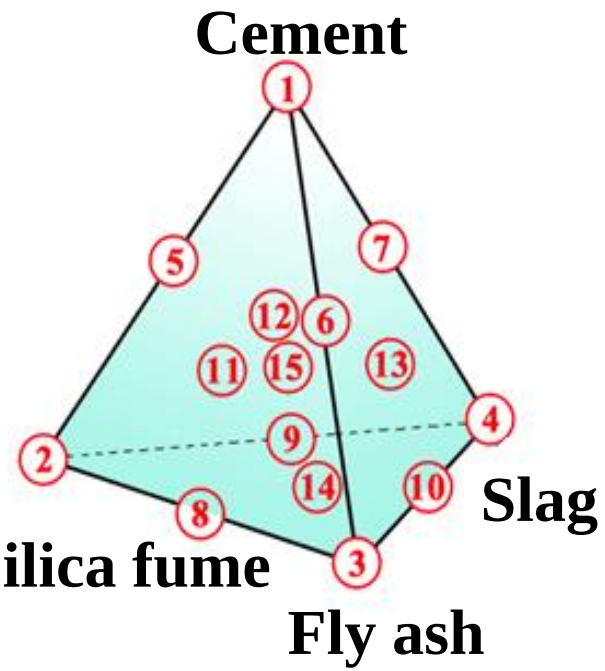
Composition of Quaternary cementitious materials

NO.	Cement	Silica fume	Fly ash	Slag
N-1	100	0	0	0
N-2	70	30	0	0
N-3	70	0	30	0
N-4	70	0	0	30
N-5	85	15	0	0
N-6	85	0	15	0
N-7	85	0	0	15
N-8	70	15	15	0
N-9	70	15	0	15
N-10	70	0	15	15
N-11	80	10	10	0
N-12	80	10	0	10
N-13	80	0	10	10
N-14	70	10	10	10
N-15	77.5	7.5	7.5	7.5



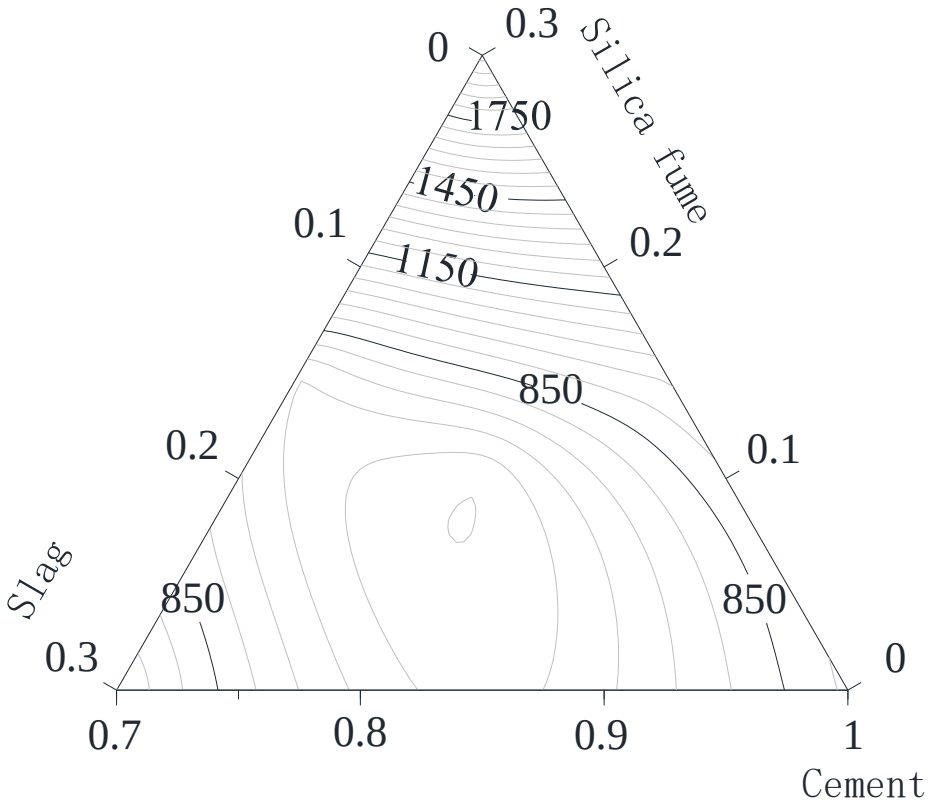
Effect of Composition on Autogenous Shrinkage

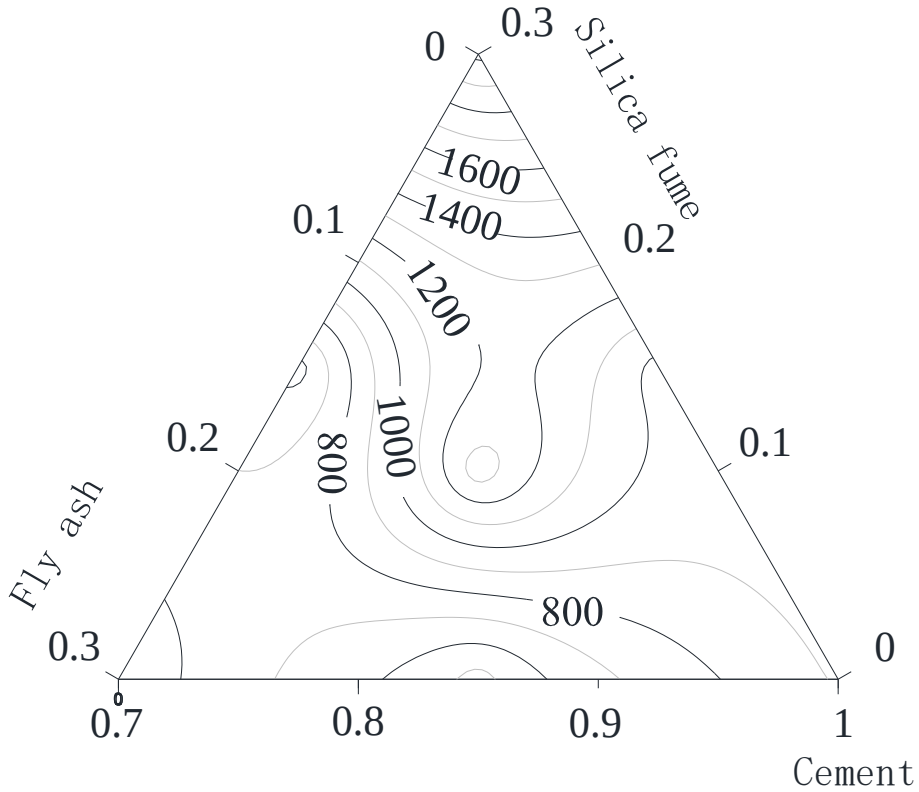




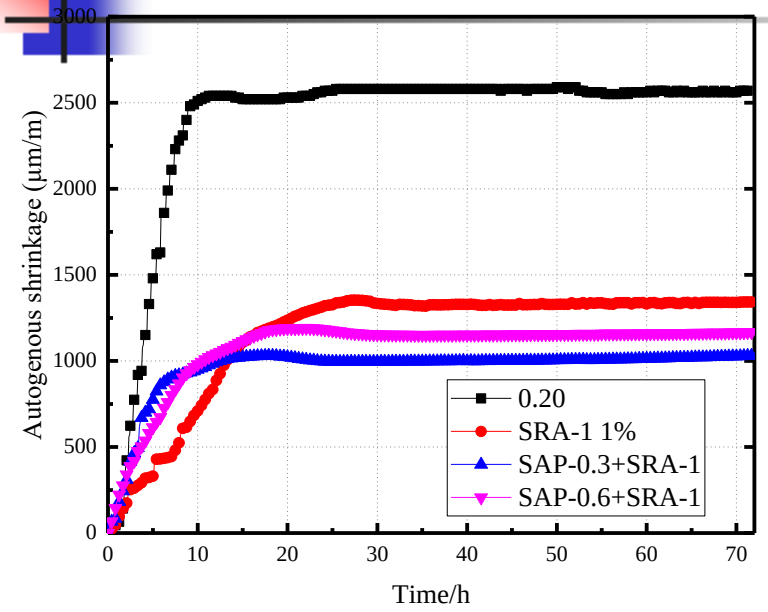
Effect of Composition on Autogenous Shrinkage

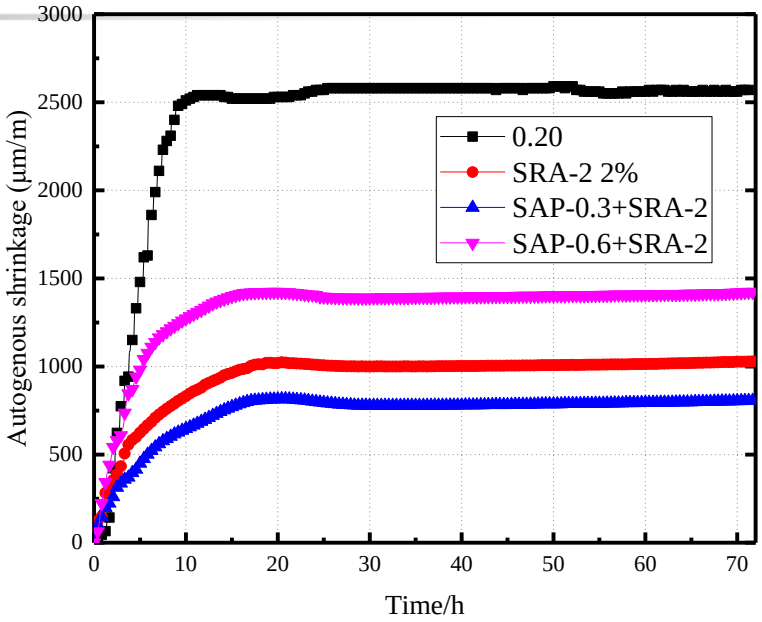
$$Y_{AS_{72}} = Y\mathbf{1} \times 10^3\, x_1 + \mathbf{2} \times 10^4 x_2 + 1.4 \times 10^4 x_3 + 1.2 \times 10^4 x_4 - 2.2 \times 10^4 x_1 x_2 - 1.9 \times 10^4 x_1 x_3 - 1.5 \times 10^4 x_1 x_4 - 7 \times 10^5 x_2 x_3 - 5.2 \times 10^4 x_2 x_4 + 1 \times 10^5 x_3 x_4 + 8.99 \times 10^5 x_1 x_2 x_3 + 2.3 \times 10^4 x_1 x_2 x_4 + 1.91 \times 10^5 x_1 x_3 x_4 + 2 \times 10^7 x_2\, x_3 x_4 - 2 \times 10^7 x_1 x_2 x_3 x_4$$

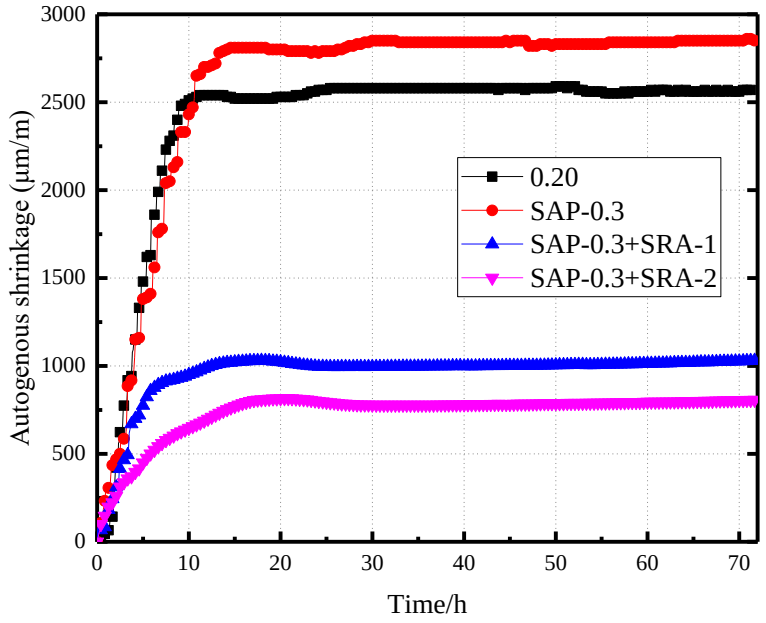


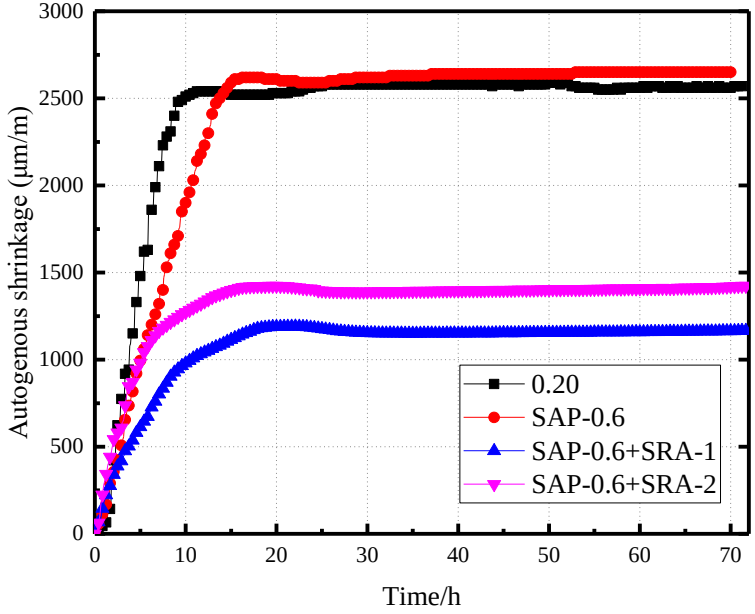


Mitigation of Autogenous Shrinkage by SAP and SRA

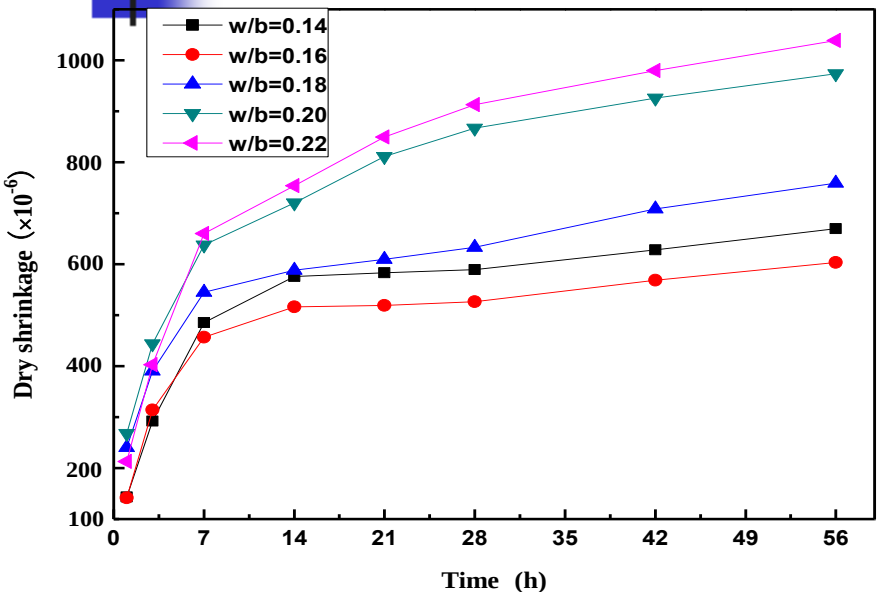


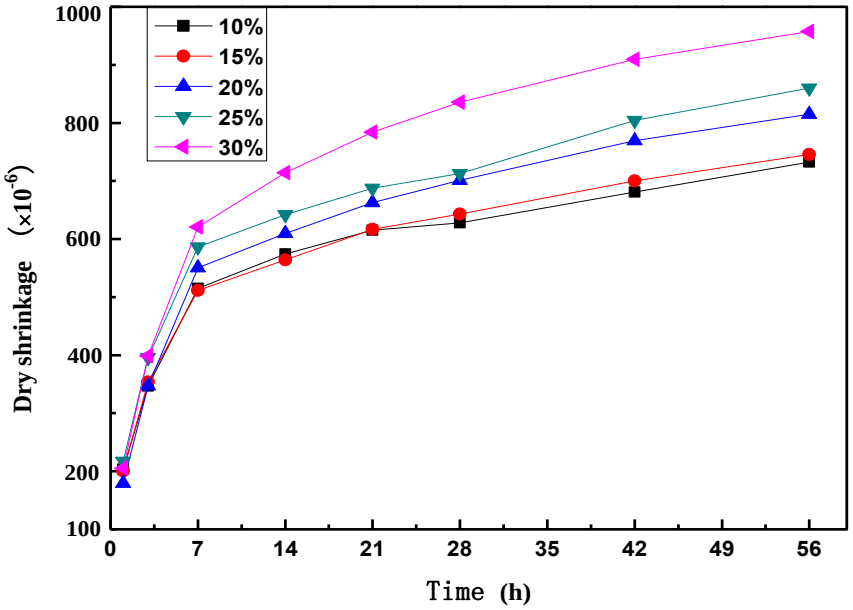


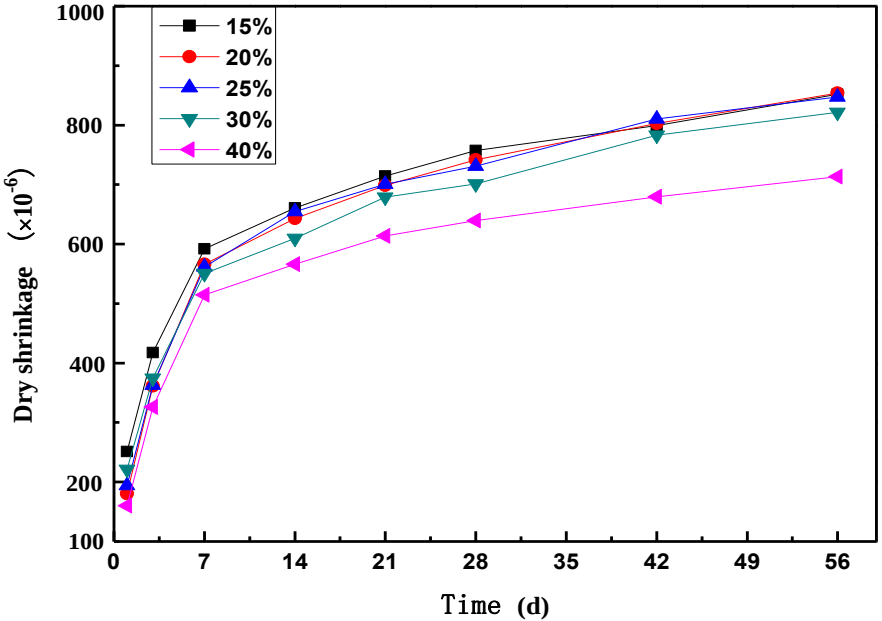


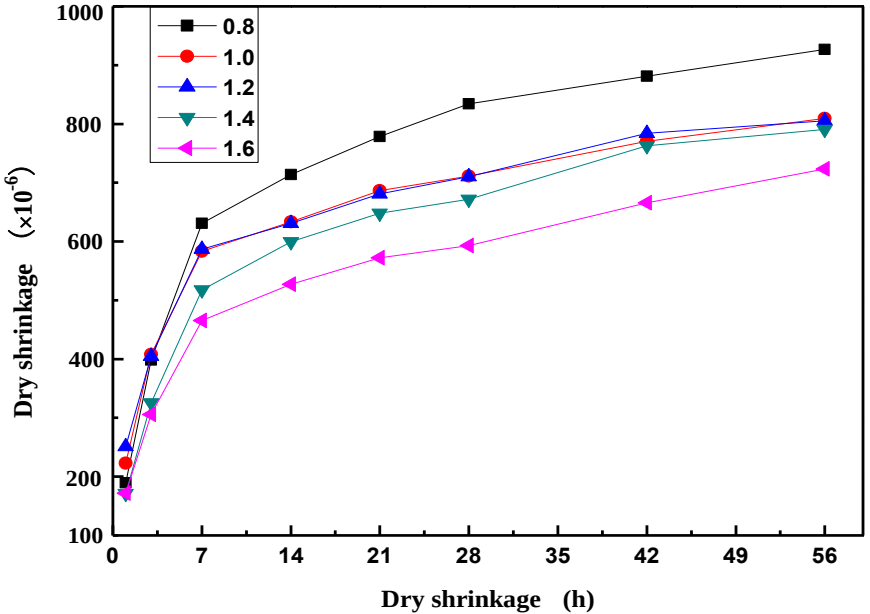


Drying shrinkage

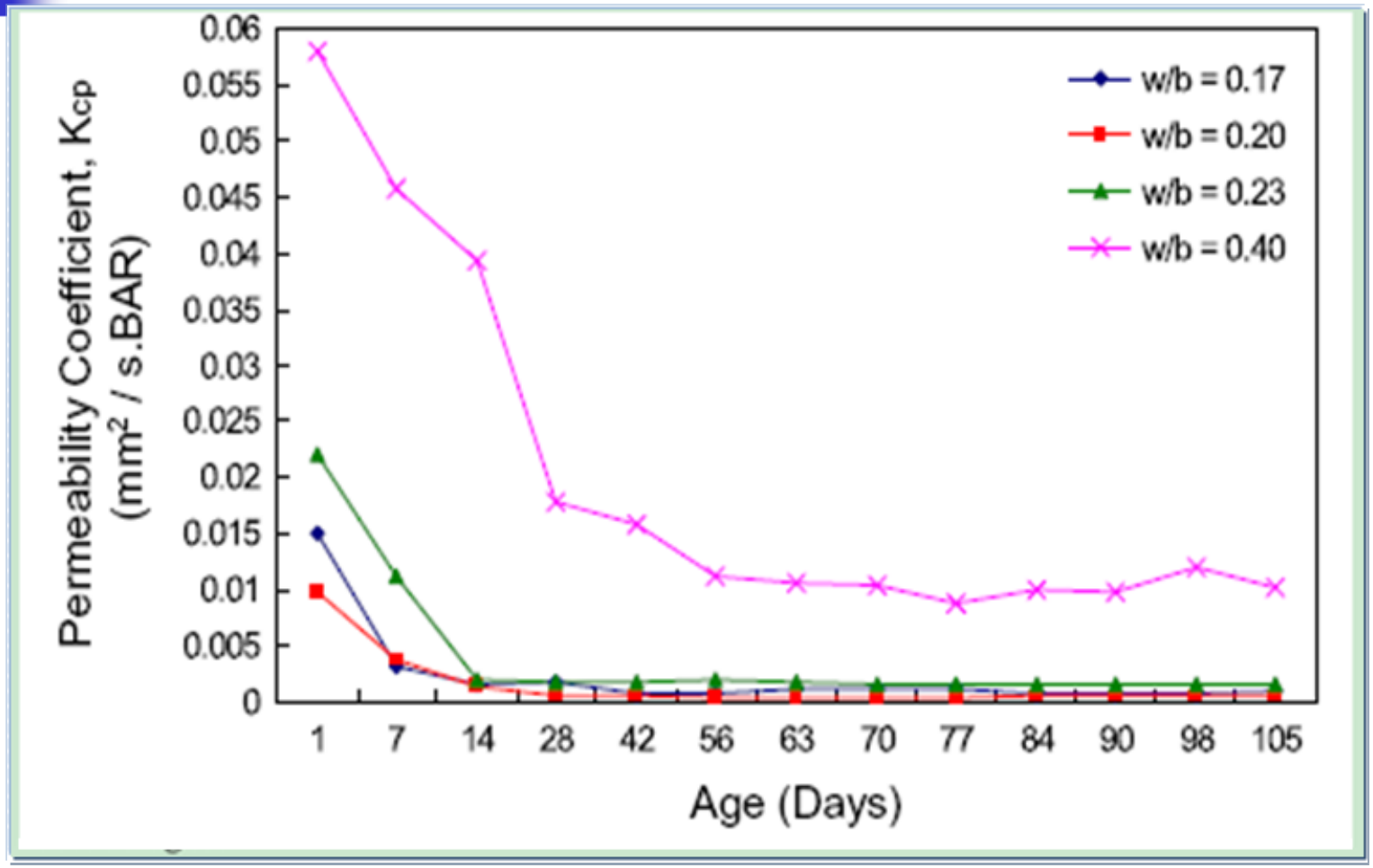






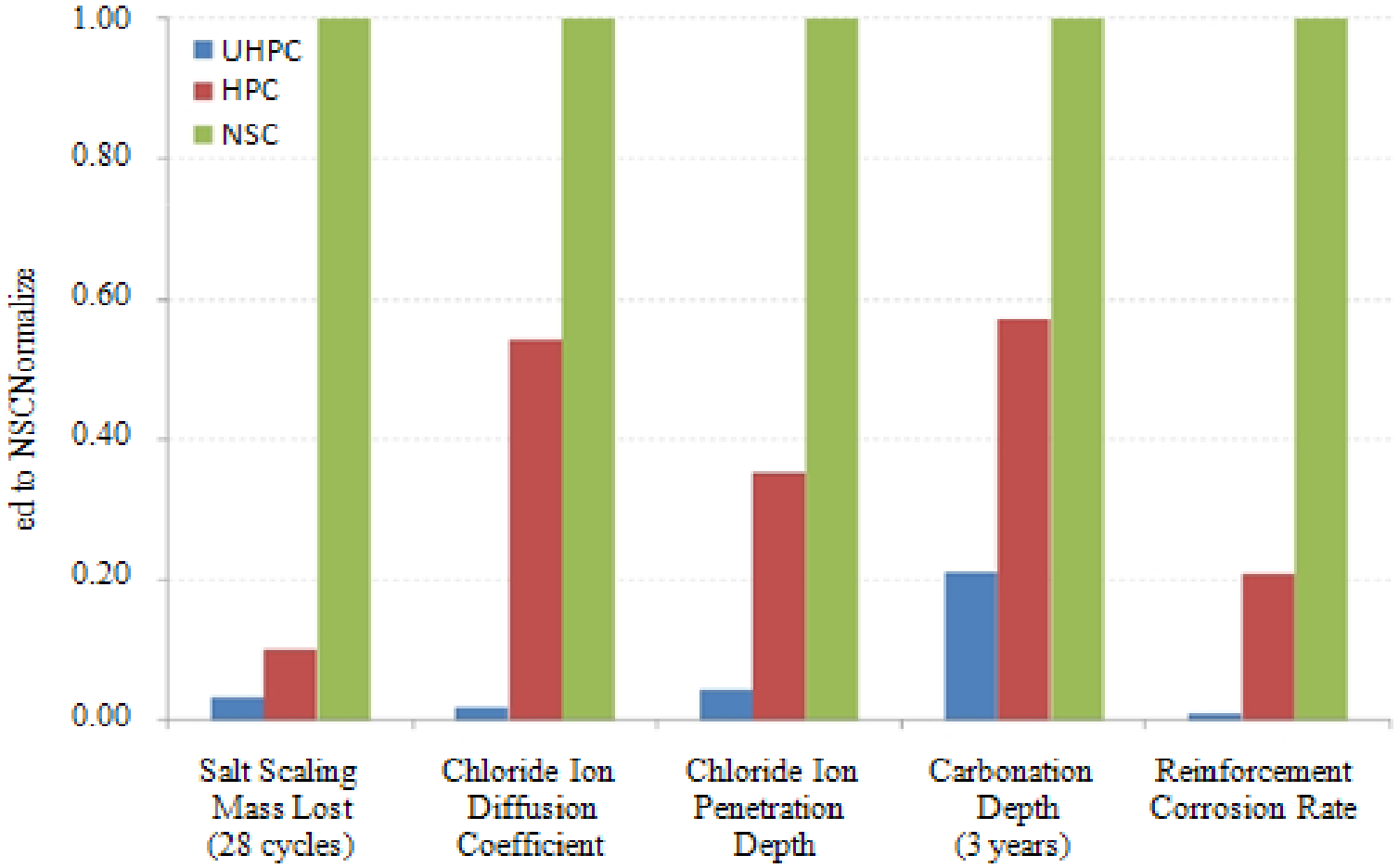


Water permeability and carbonation



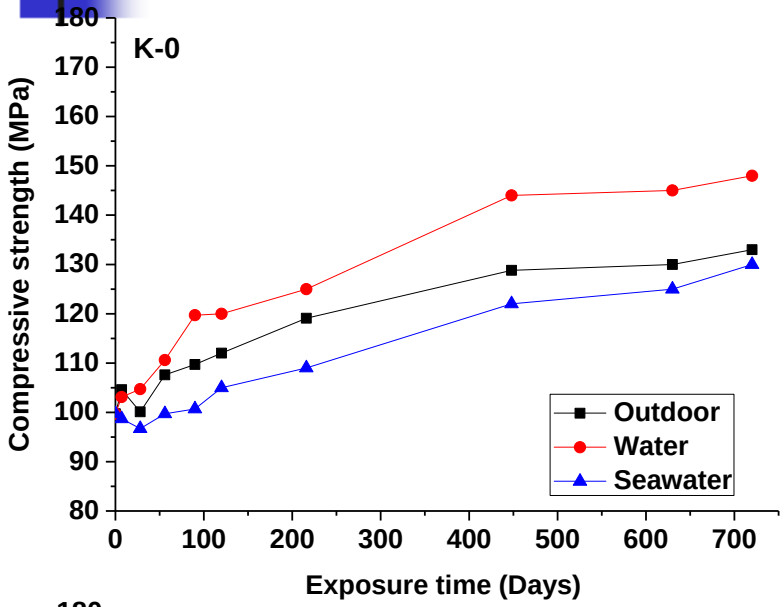
W/B < 0.23, the permeability is extremely low; no carbonation could be detected after 28 days of exposure to 20%CO2.

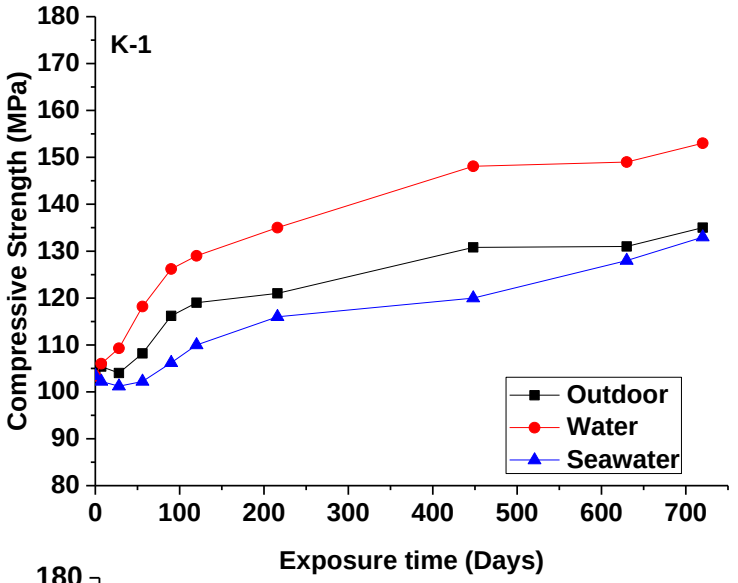
Durability

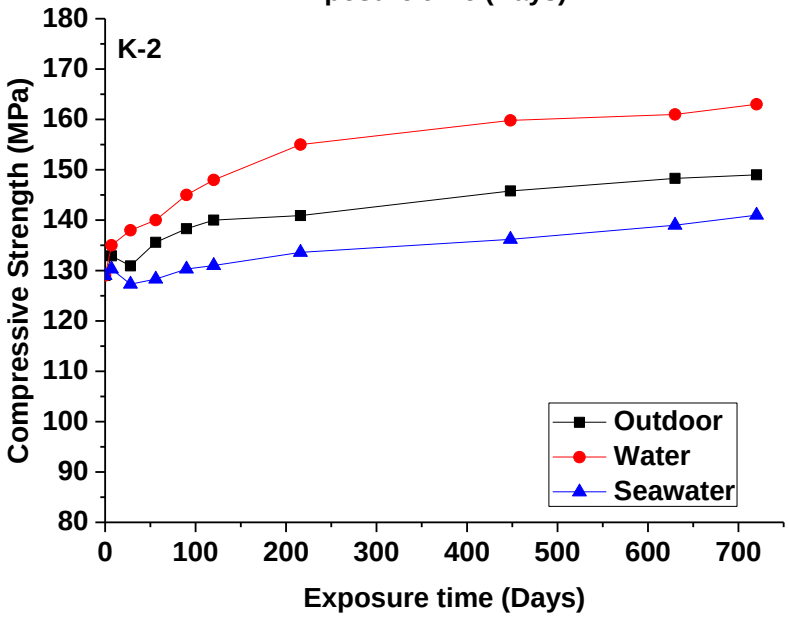


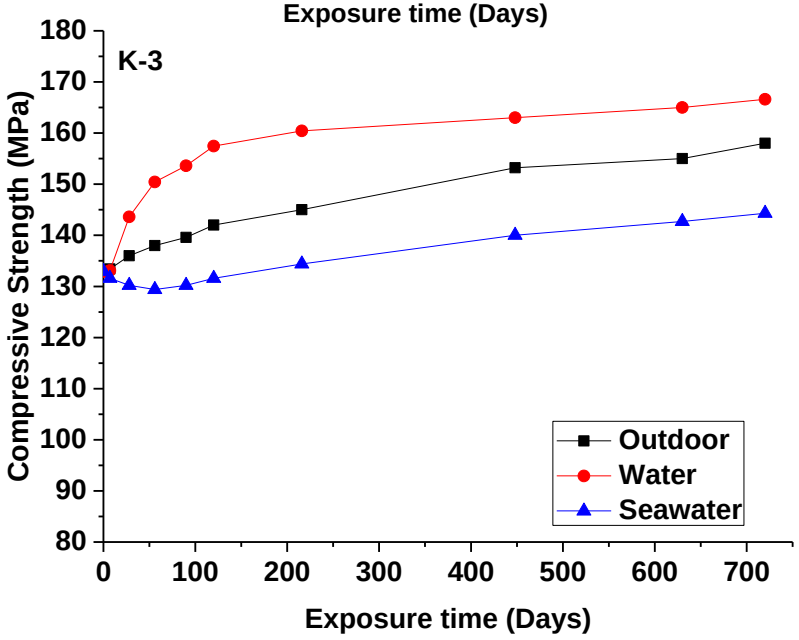
Durability comparison among UHPC, HPC and OC

Compressive Strength of Slag-Based UHPC in Different Environments

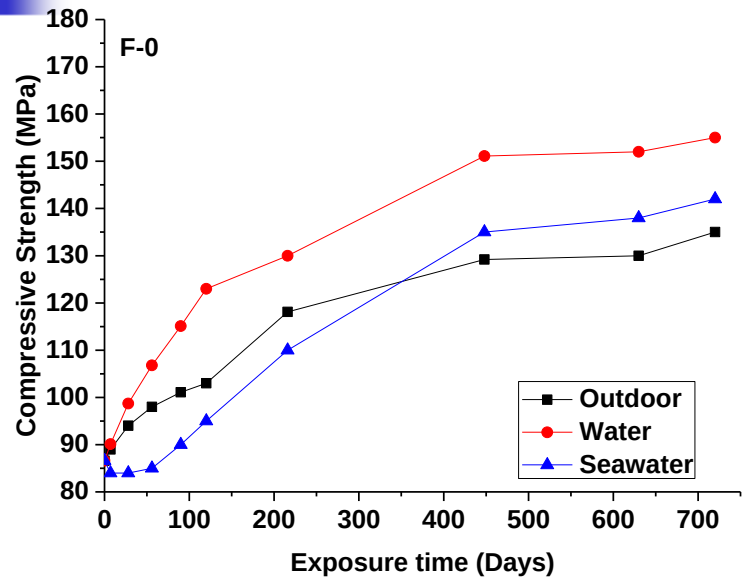


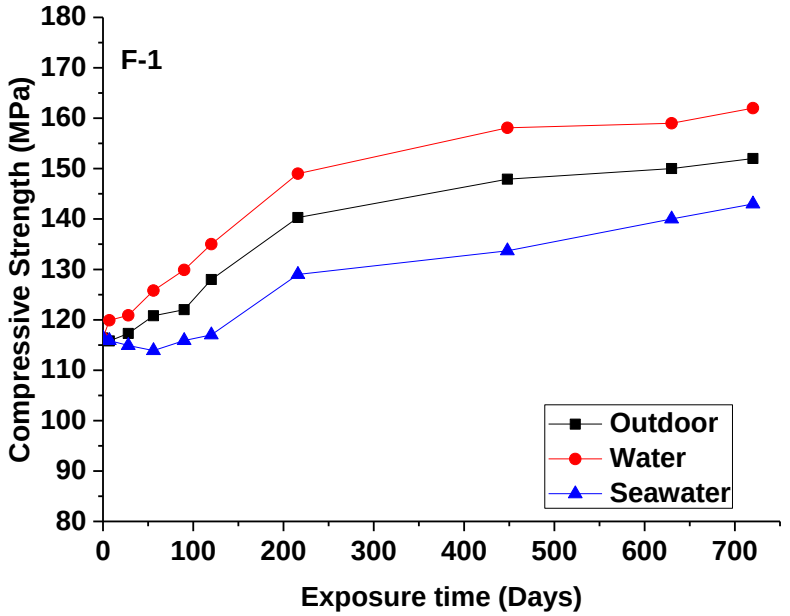


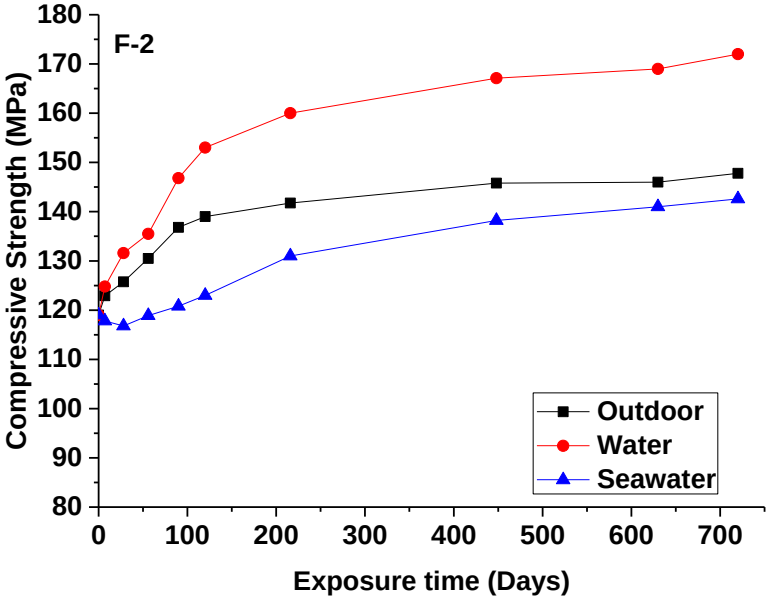


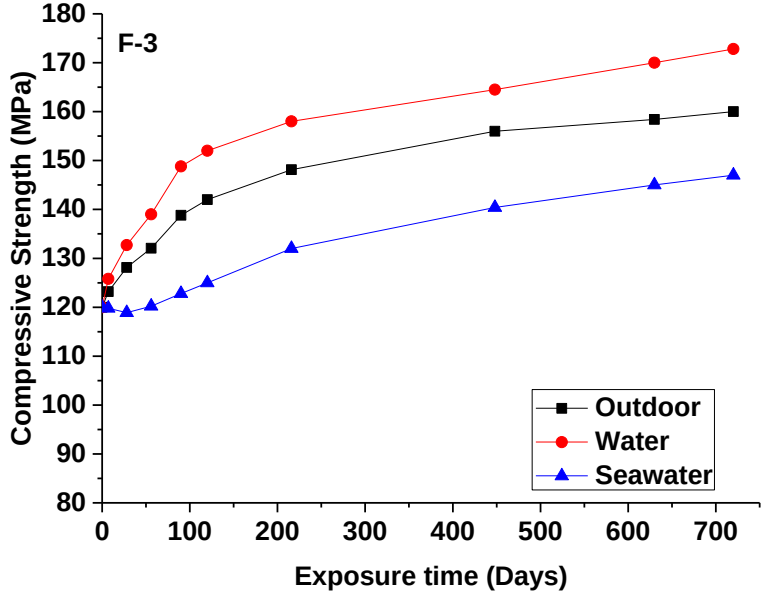


Compressive Strength of Fly Ash-Based UHPC in Different Environments

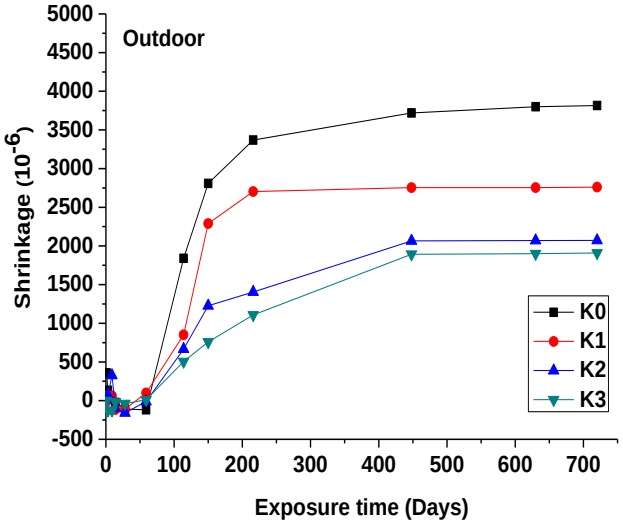


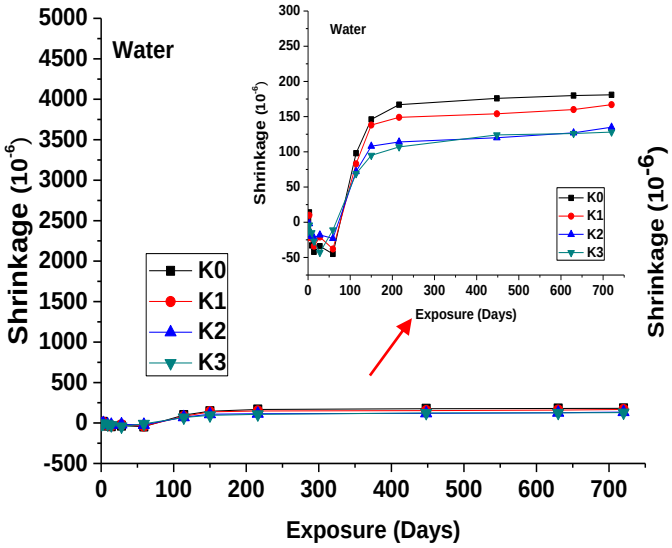


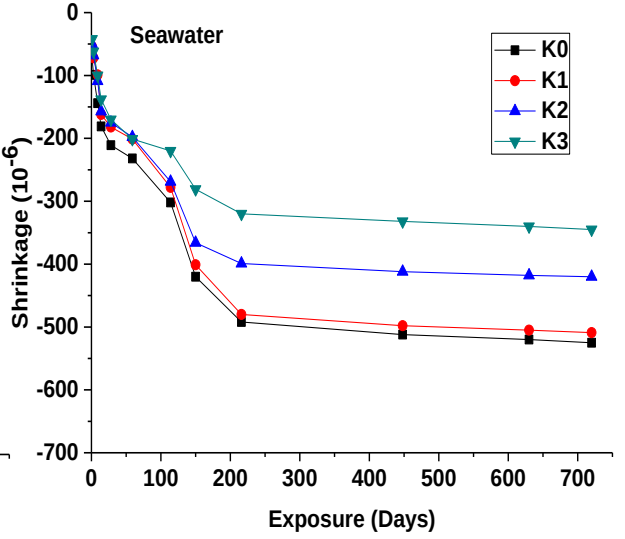


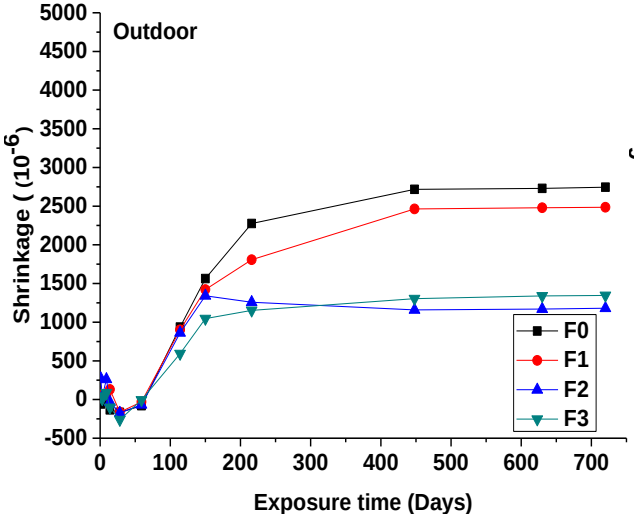


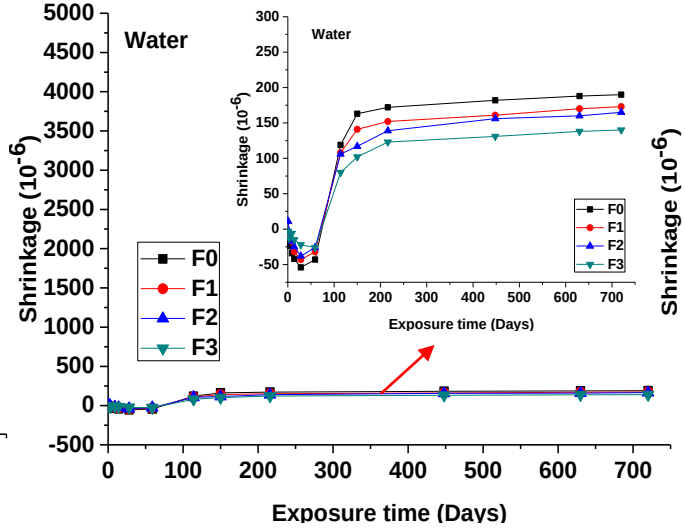
Dimensional Stability of UHPC in Different Environments

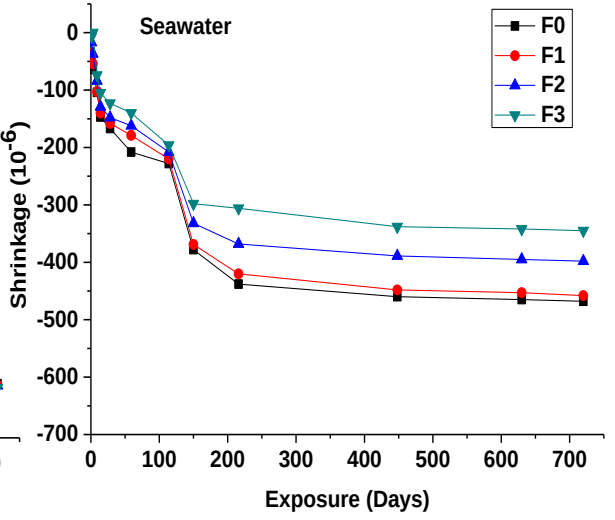




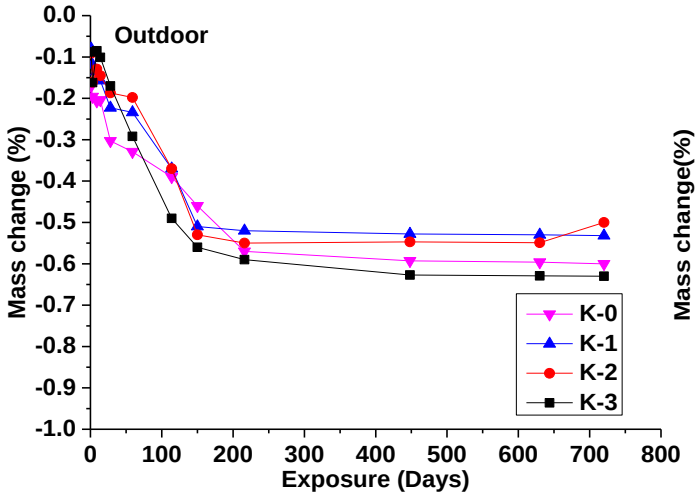


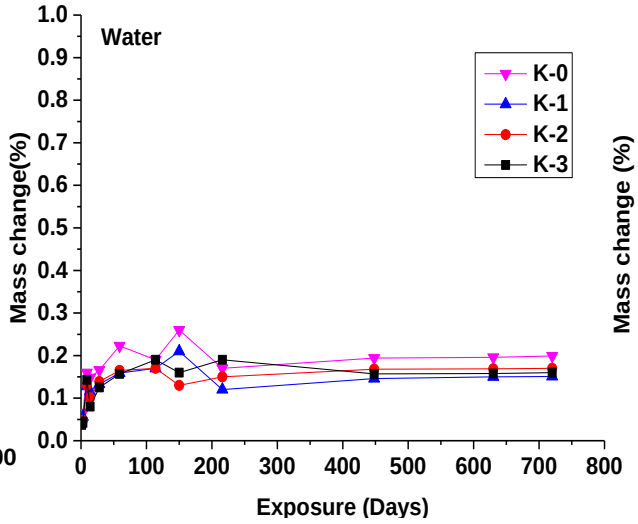


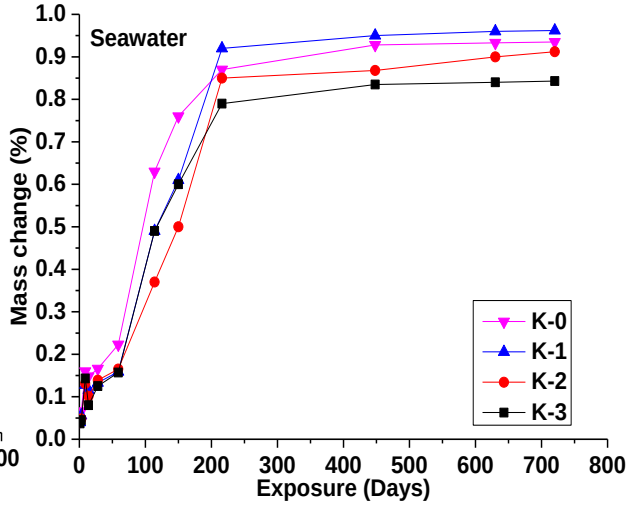


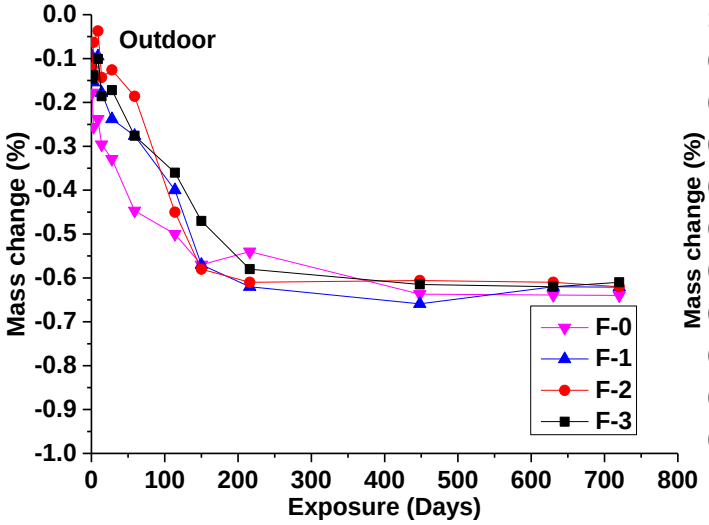


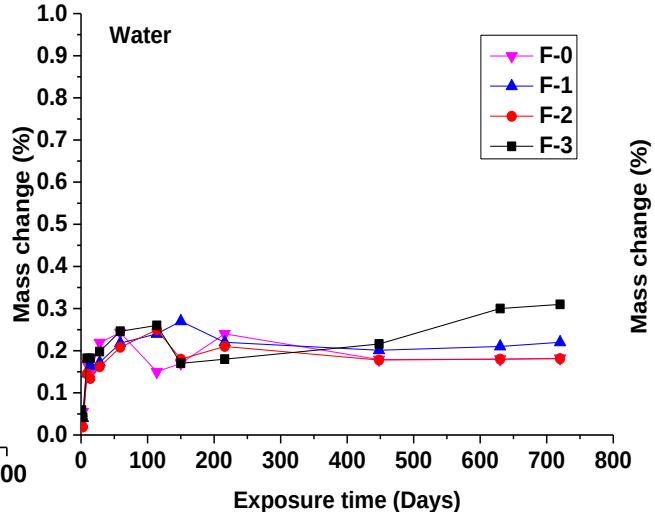
Mass Change of UHPC in Different Environments

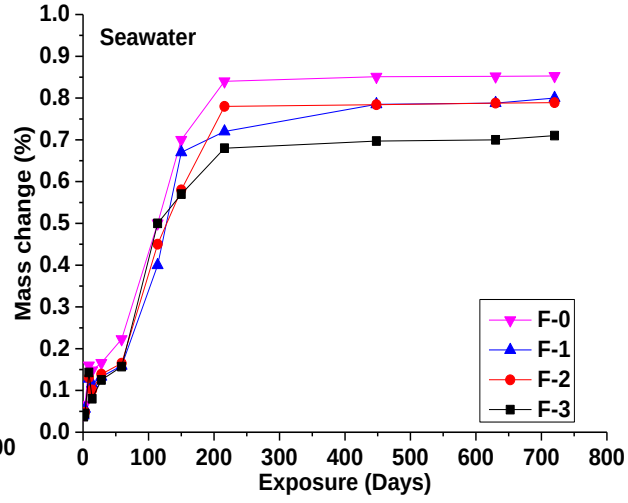




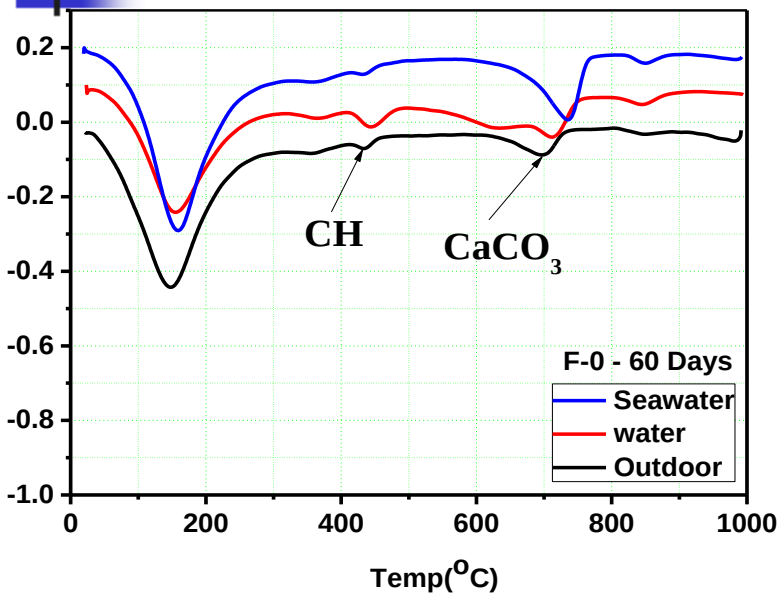


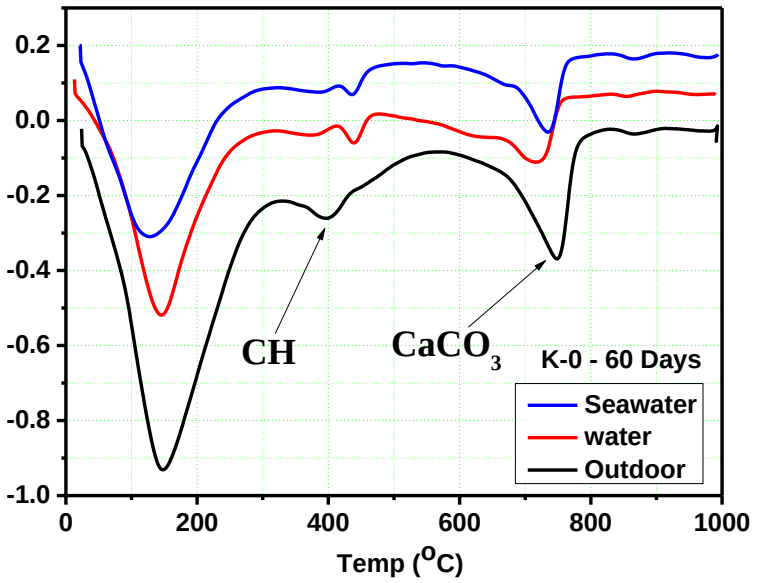


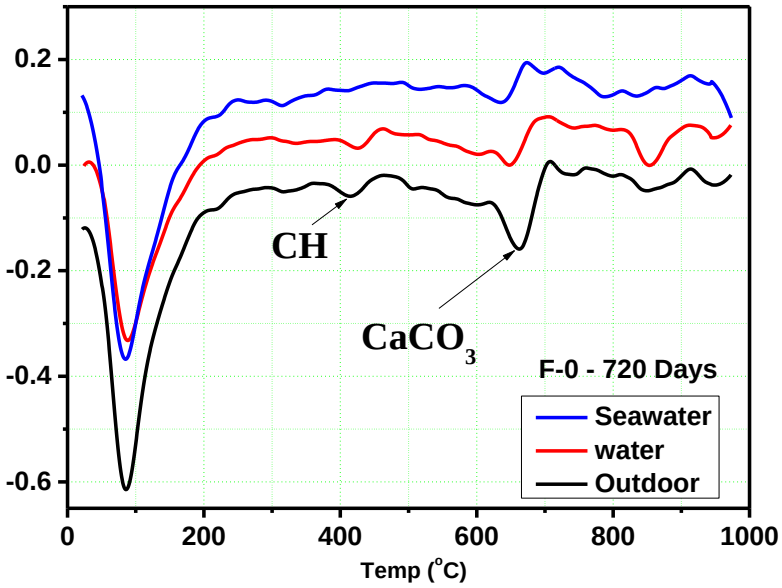


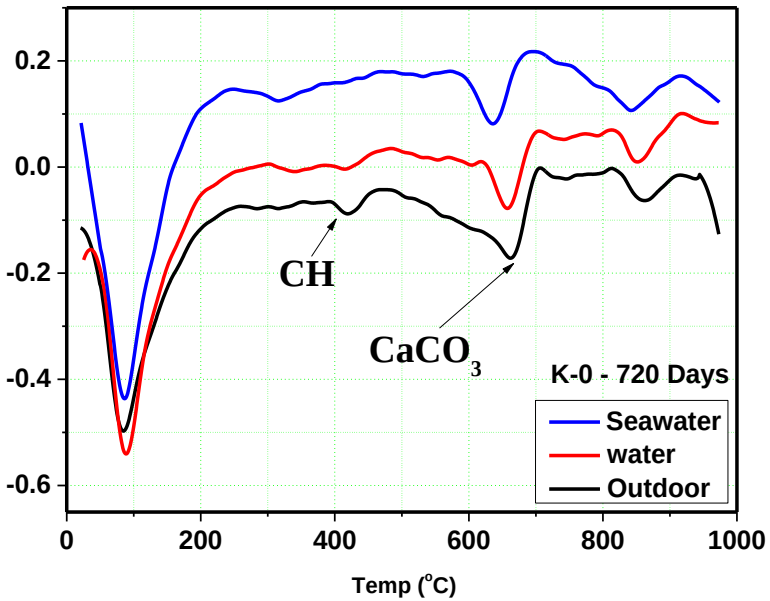


TGA of UHPC at Different Ages in Different Environments



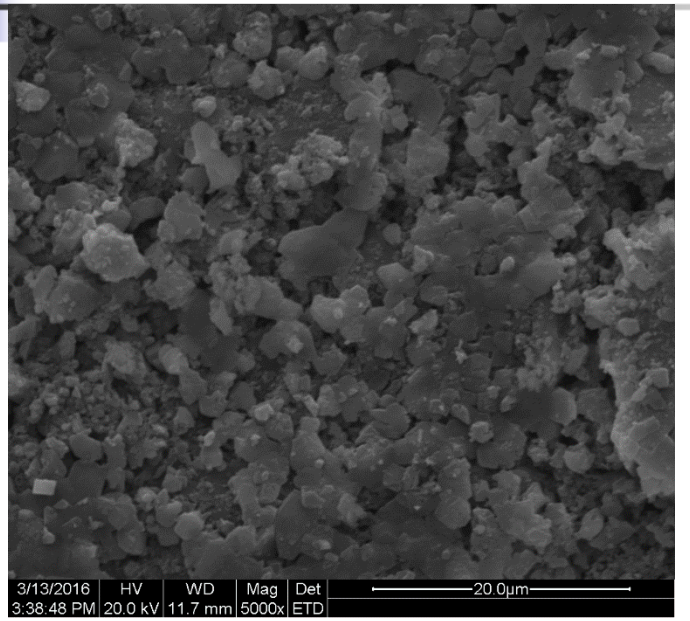


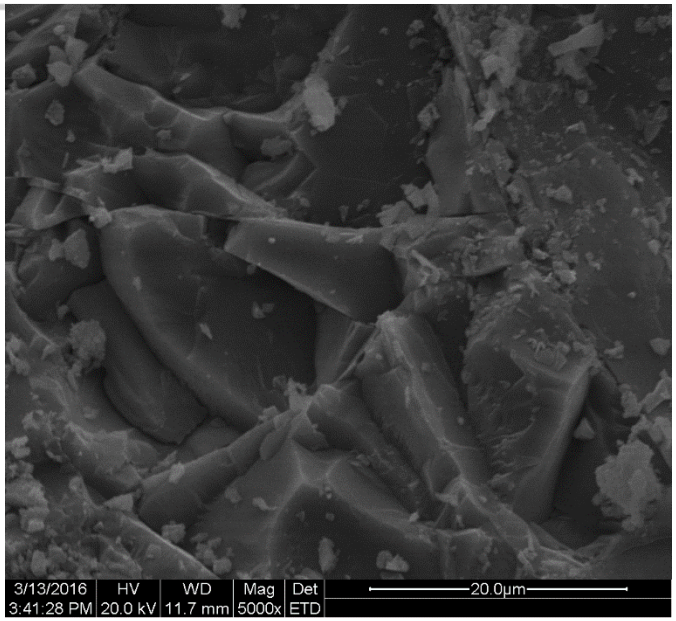




SEM Pictures of UHPC at 360 d

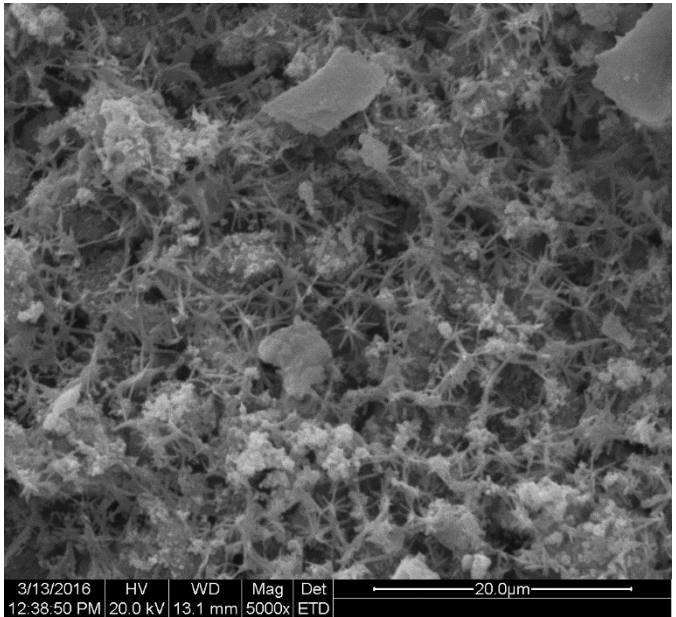
Water

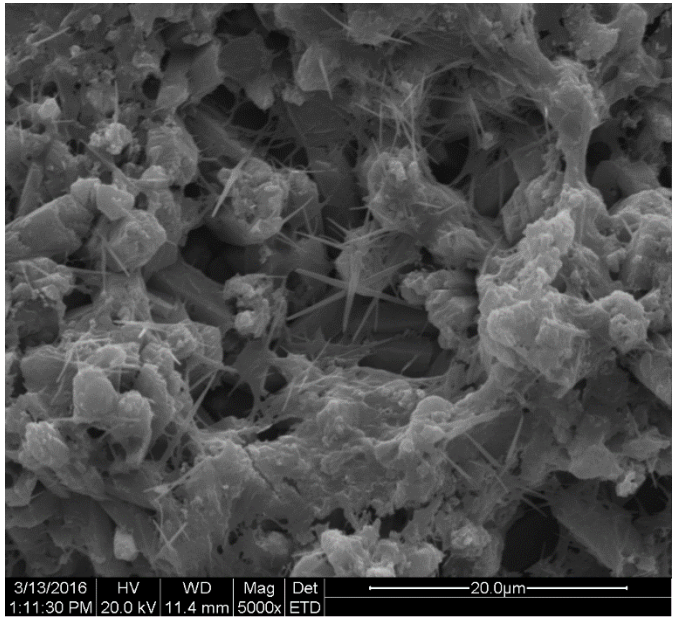




Water, Inside 5mm

Seawater

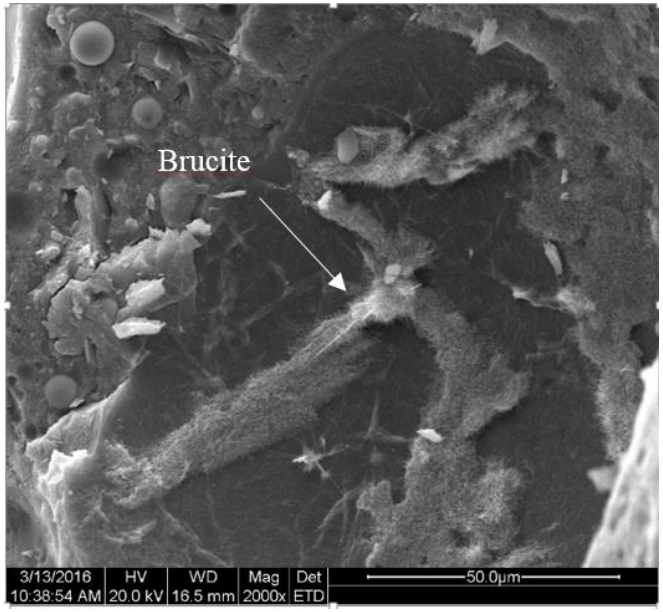


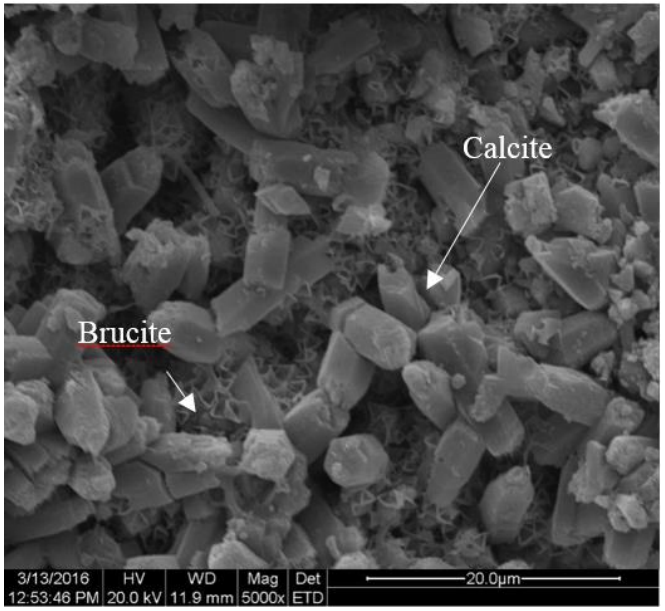


Seawater, Inside 5mm

Microstructure of UHPC at 720 Days in Different Environments

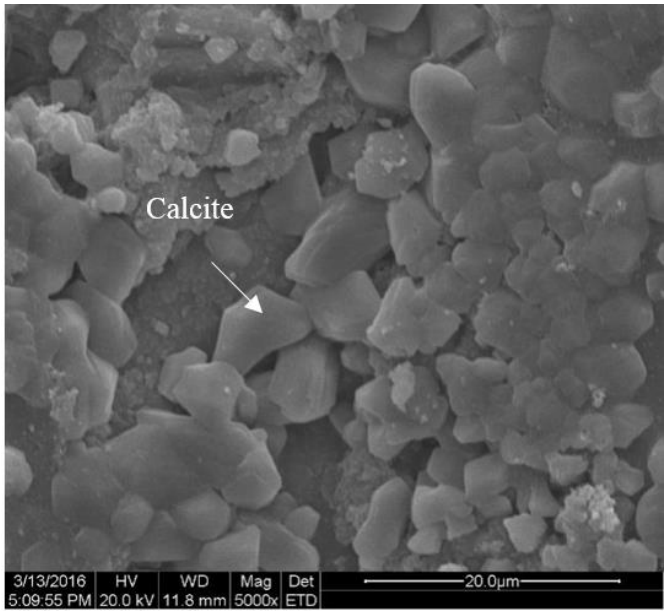
Seawater





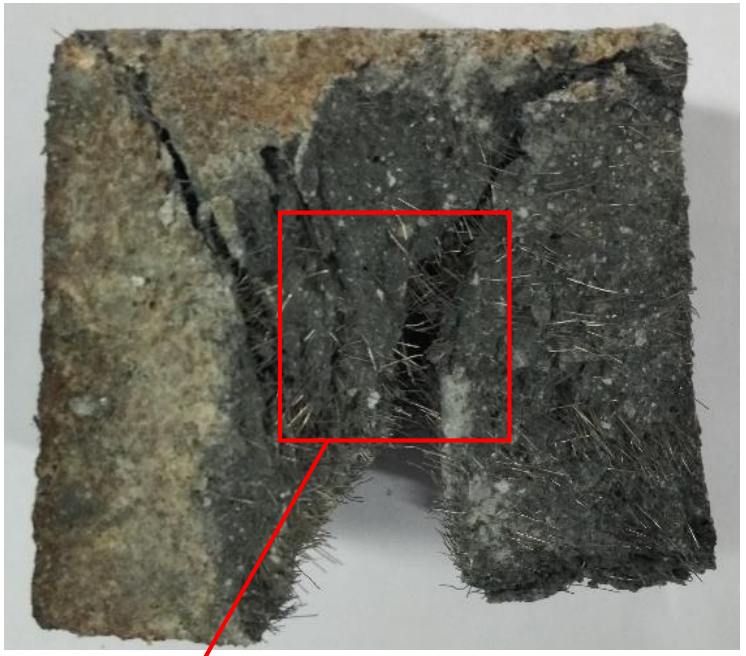
Seawater, Inside 5mm

Outdoor

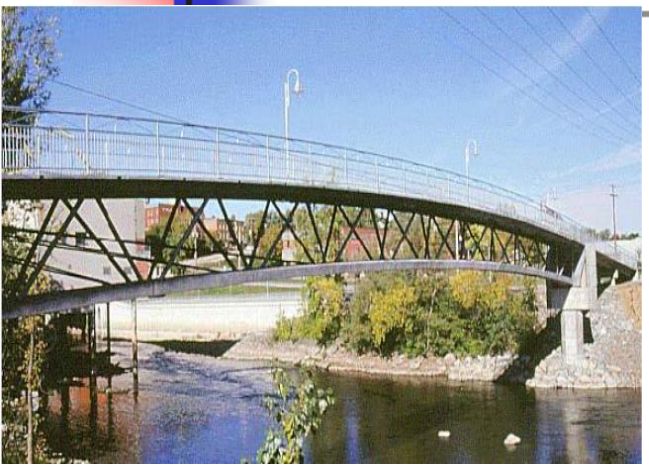


Outdoor, Inside 5mm

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

- **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

- A Chinese book entitled "Reactive Powder Concrete" published in 2013;
- A Chinese book entitled "Ultra high performance Cement-based Materials" published in 2015;
- Chinese National Standard GB/T 31387-2015 "Reactive Powder Concrete" issued in 2015;
- 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.

ICS 91.100.30
Q 13

GB

中华人民共和国国家标准

GB/T 31387—2015

工程试验检测群：94527577

活性粉末混凝土

Reactive powder concrete

2015-02-04 发布　　2015-11-01 实施

中华人民共和国国家质量监督检验检疫总局
中国国家标准化管理委员会　发布

Applications of UHPC in China

- High speed railway/Subway cable ditich system;
- Lightweight composite bridge decks;
- Precast bridge girders/piers;
- Precast assembled bridge;
- High performance grout for different applications.

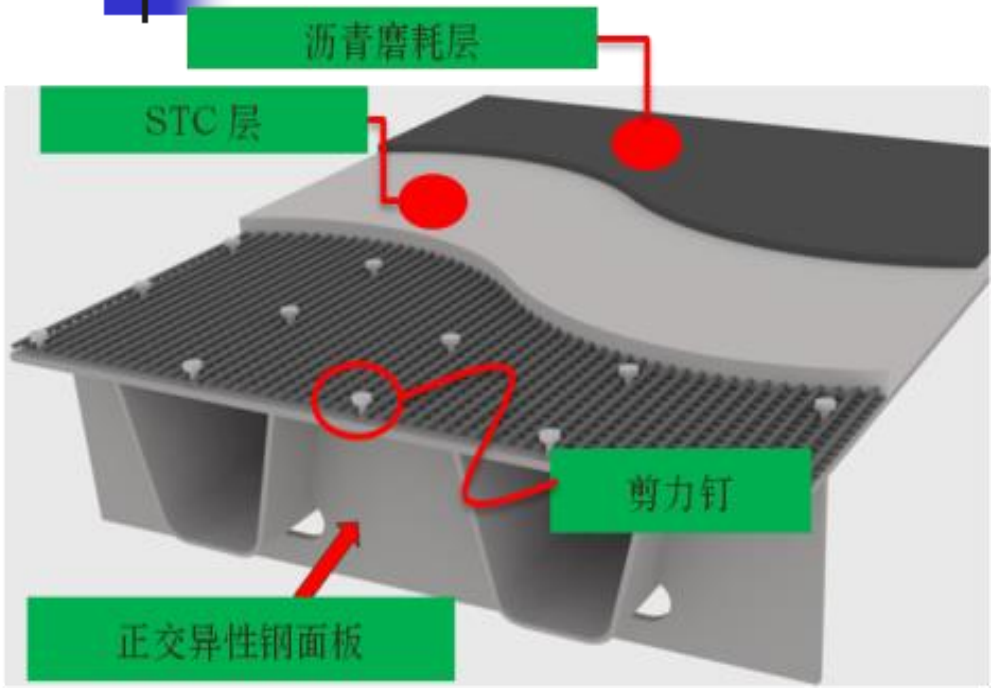
Applications of UHPC in China

- High speed railway/Subway cable system

- **UHPC cover has replaced conventional concrete cable ditch system in highspeed railway in China since 2009;**
- **21.4 million m^2 UHPC has been used in 16,000 km high speed railway till March 2015;**
- **A total of 535,000 m^3 of UHPC has been used for those;**

Applications of UHPC in China

- Lightweight Composite Bridge Deck

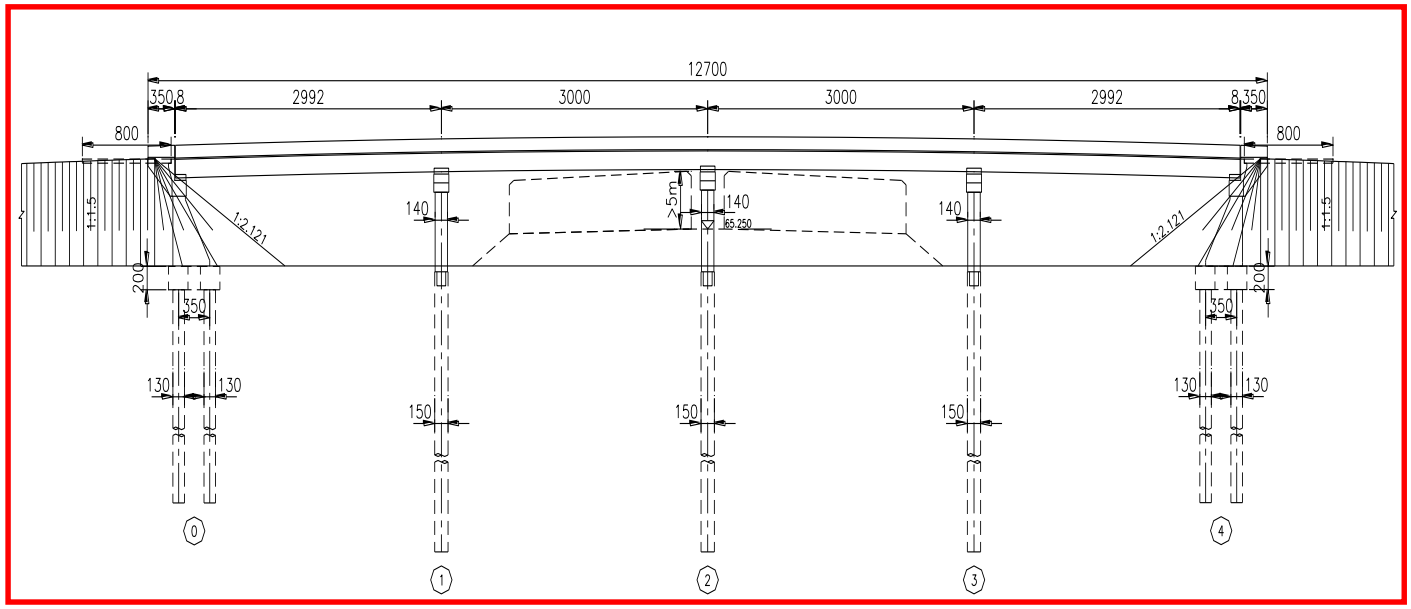


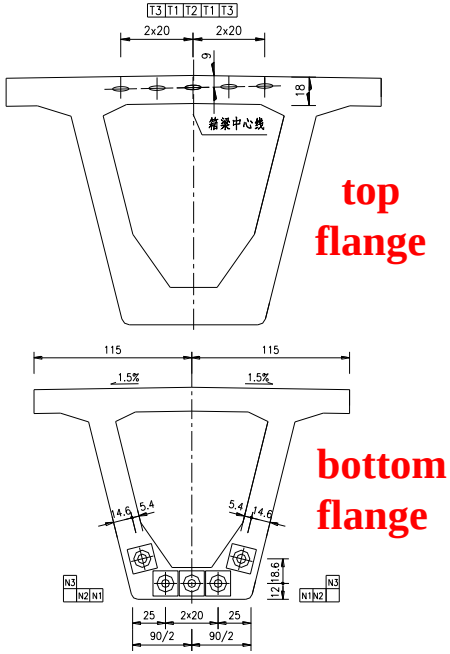
Ma Fangshan Bridge

Applications of UHPC in China

- Highway Bridge Girders

- Fisrt 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}=130MPa (100×100×100mm) and E_s=40Gpa (100×100×300mm);
- Presress UHPC girders, prestressed as normal PC girders, erected on the piers and abutments;





top flange

bottom flange

Applications of UHPC in China

- Highway Bridge Girders

Mixture Proportion of UHPC (kg/m^3)

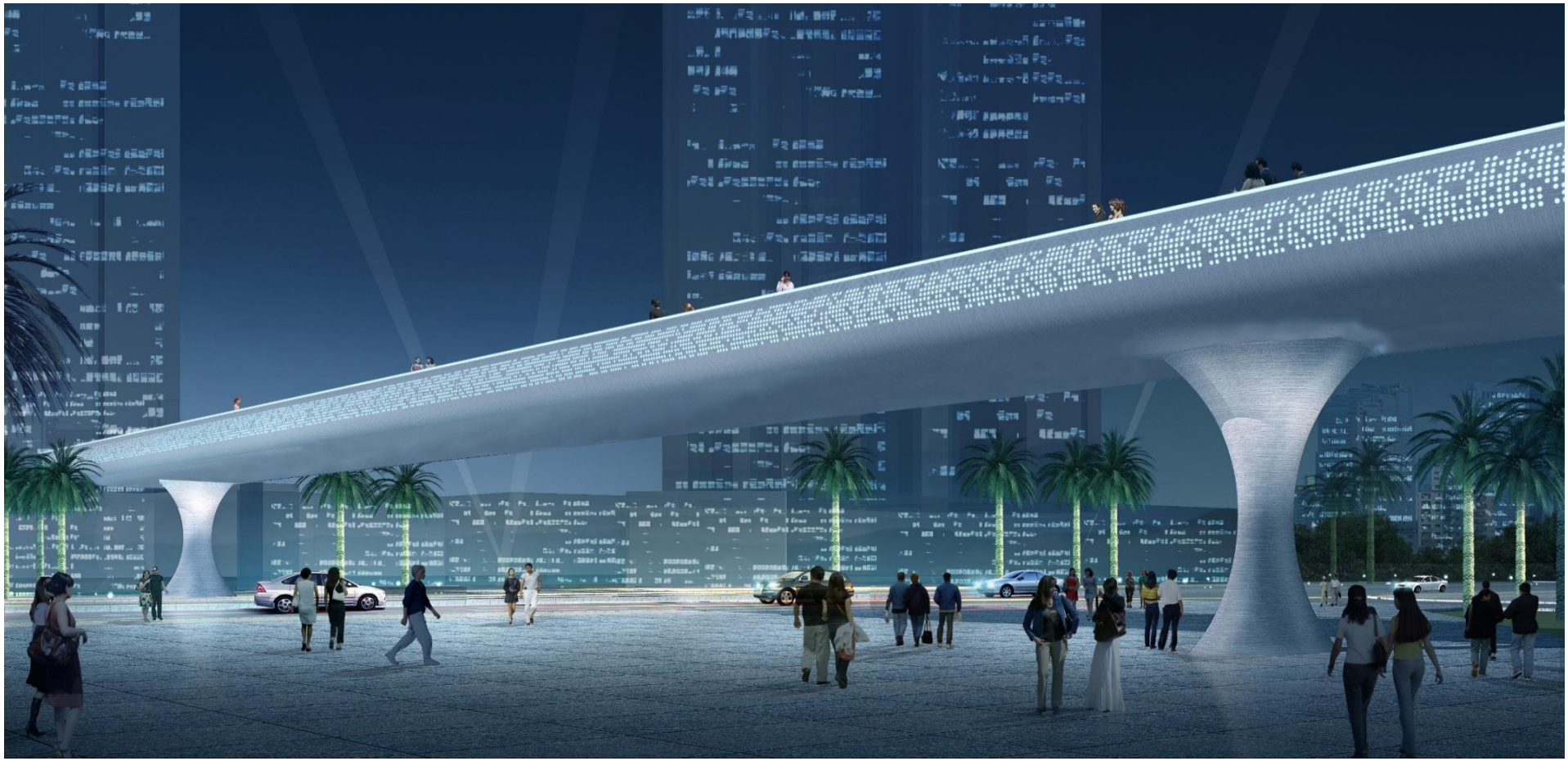
Cement	Silica Fume	Sand			Superplasticizer	Steel Fiber	Water
		Coarse sand	Medium sand	Fine sand			
851	255	212	530	318	44	157(236)	155

Precast Cast-in-situ

1. After casting, t ≥ 6h, T ≥10℃and RH ≥ 60%;
2. Then steam curing at T ≥ 90℃ and RH ≥ 95% for 72h (heating rate ≲12℃/h and cooling rate at ≲15℃/h);
3. ≥ 7d of natural curing after steam curing;
4. Girders were jointed together by in-situ cast UHPC and cured at T=70±3℃ for 72h.

Applications of UHPC in China

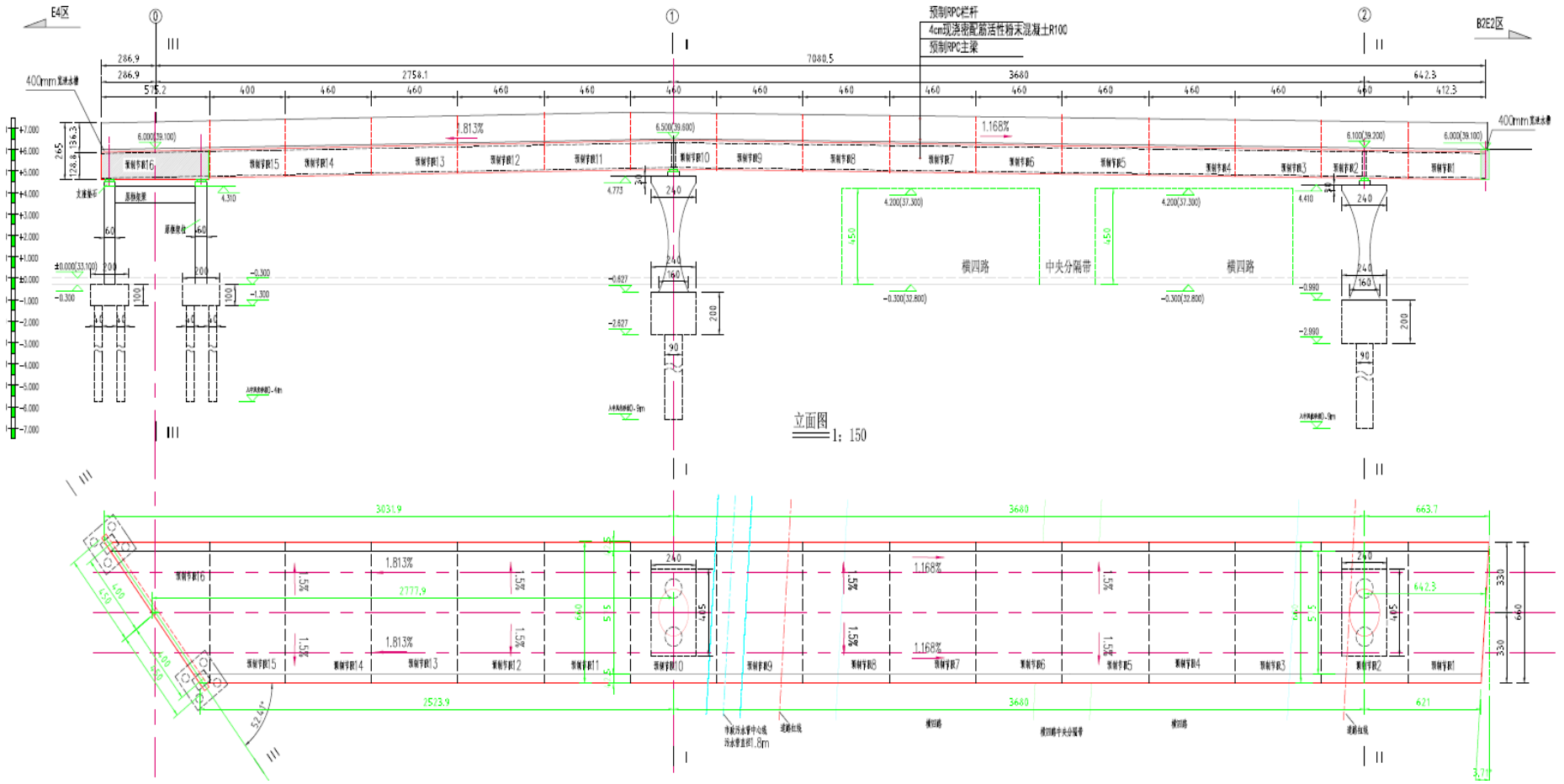
-Fully Precast Assembled Bridge in Changsha



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

Applications of UHPC in China

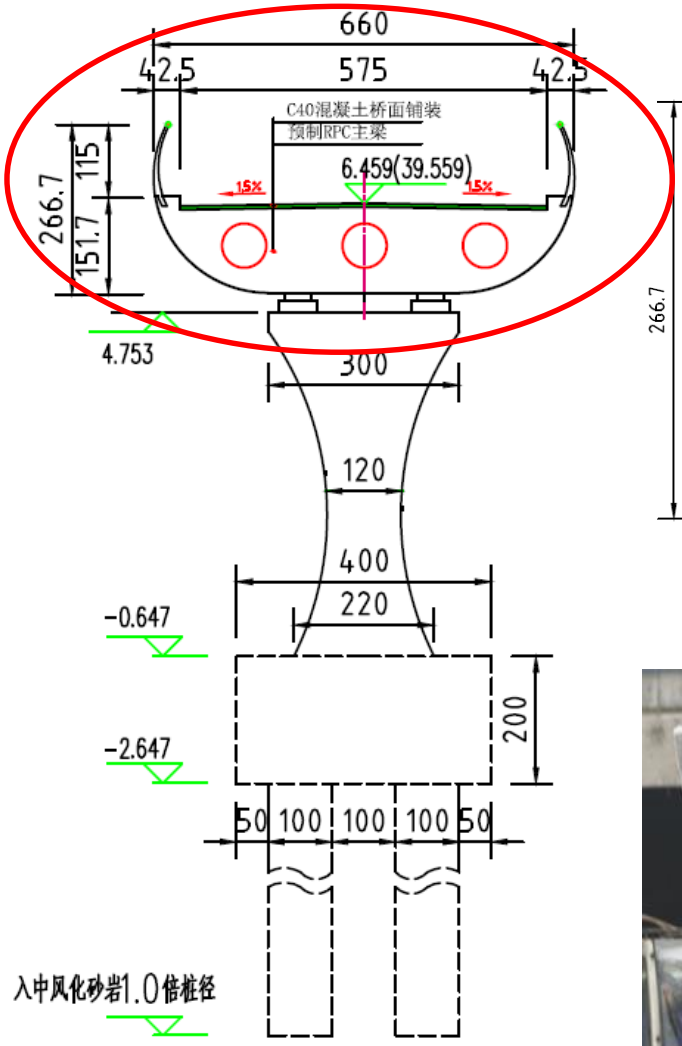
- Precast Assembled Bridge in Changsha

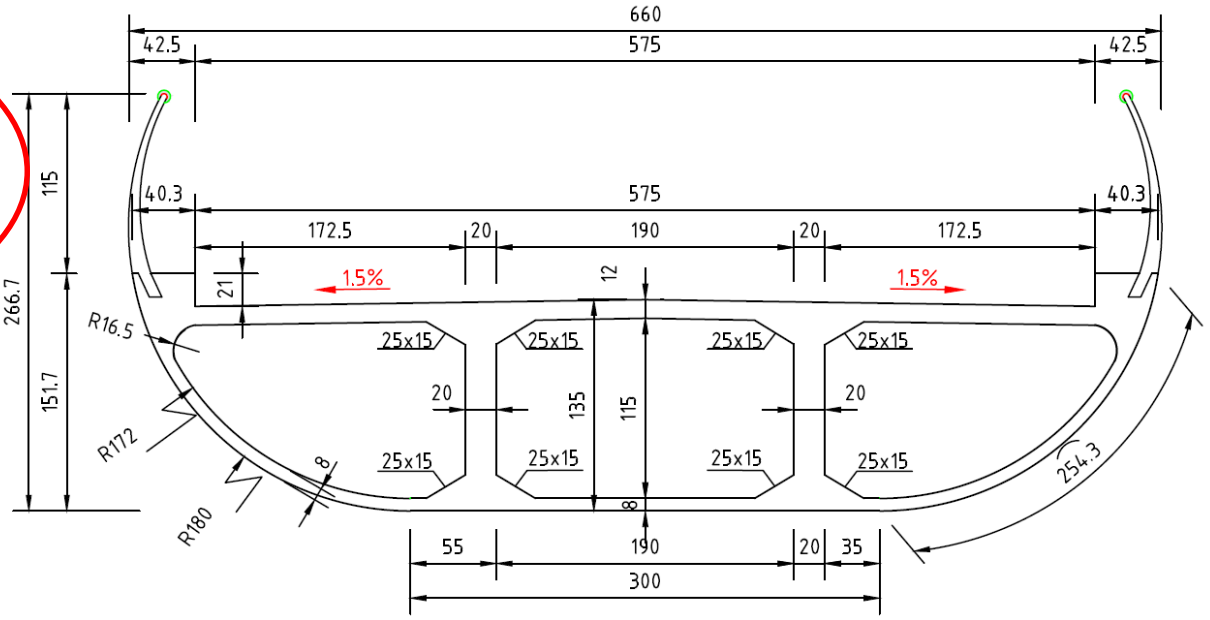


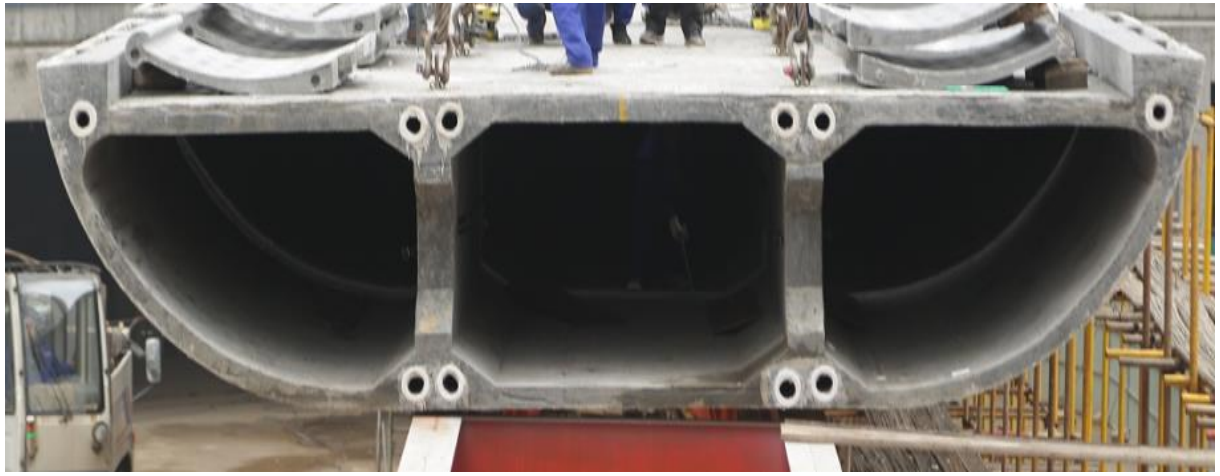
36.8m+27.6m+6.4m=70.8m

Applications of UHPC in China

- Precast Assembled Bridge in Changsha

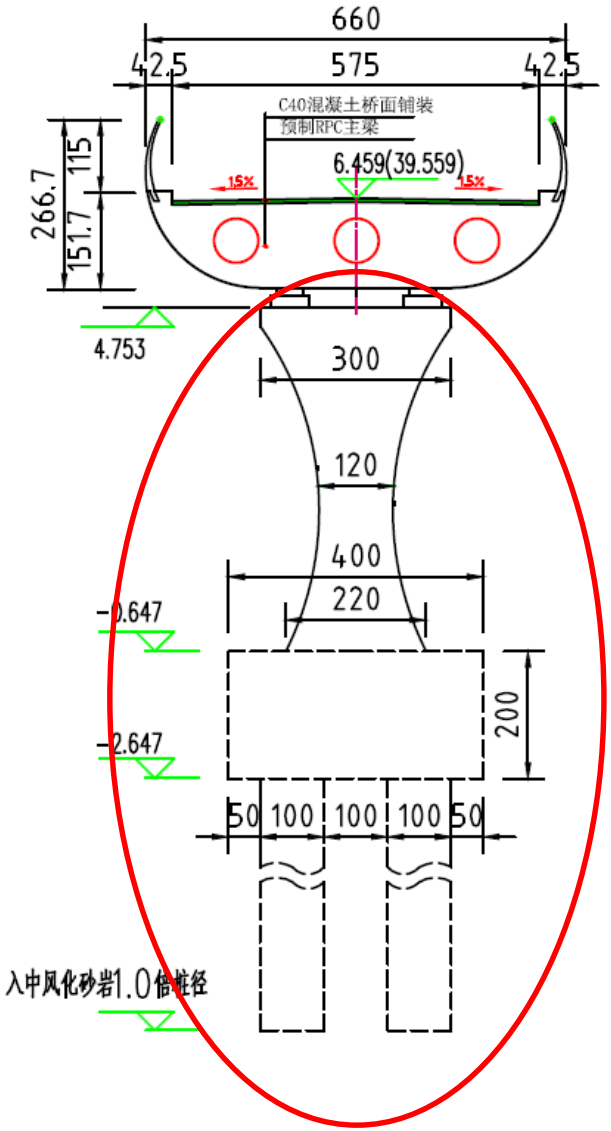


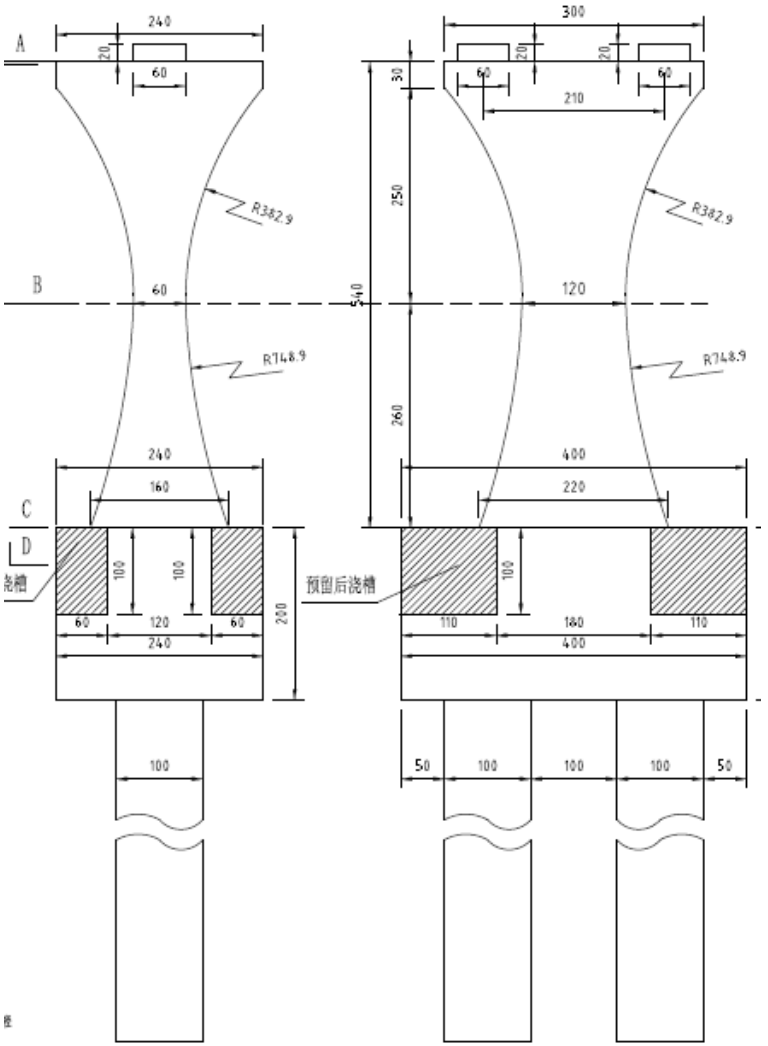


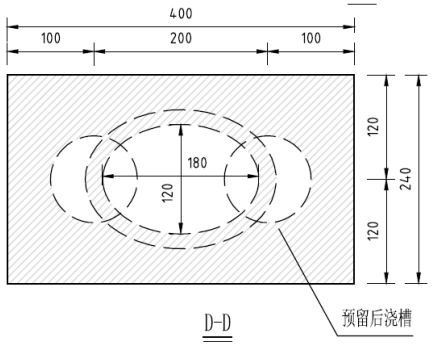


Applications of UHPC in China

- Precast Assembled Bridge in Changsha



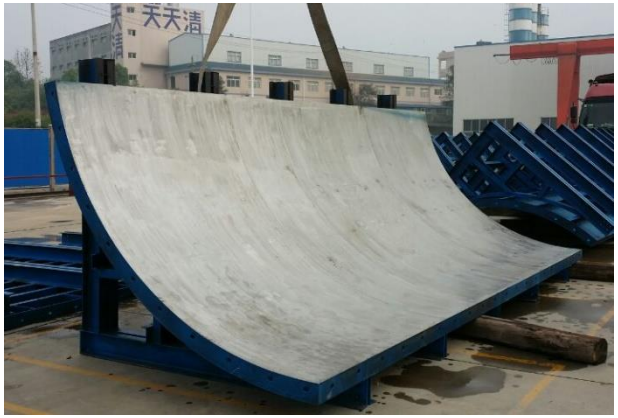




单位：cm

Applications of UHPC in China

- Precast Assembled Bridge in Changsha



Applications of UHPC in China

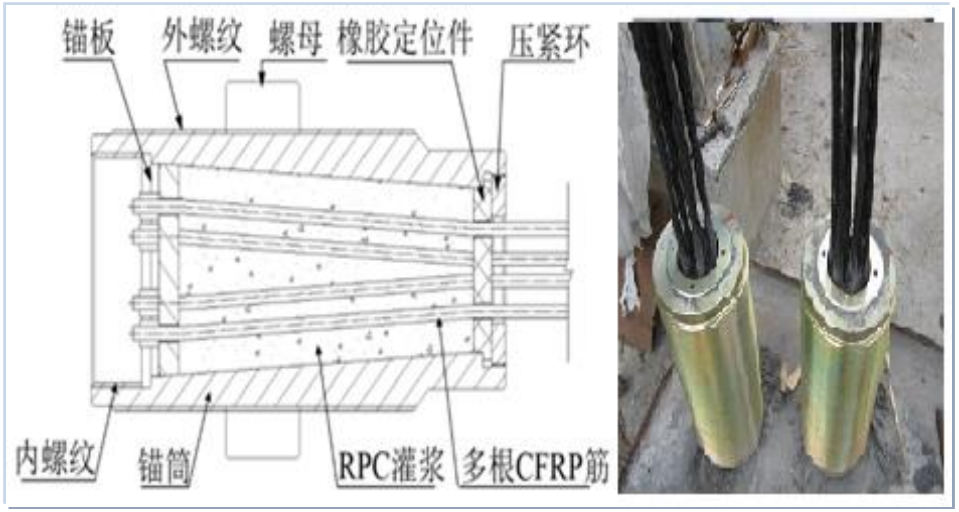
- Precast Assembled Bridge in Changsha

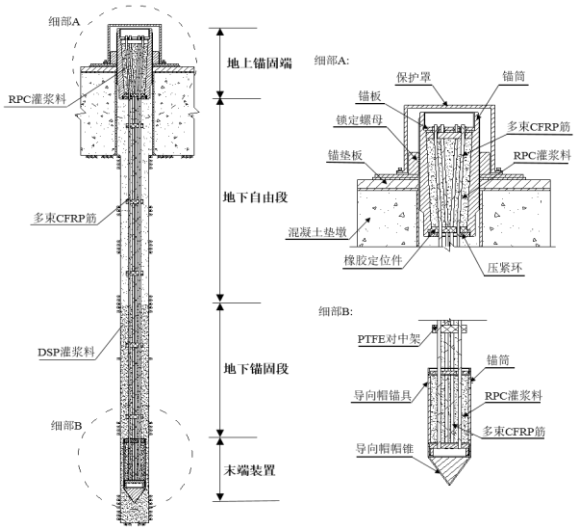
Applications of UHPC in China

- Precast Assembled Bridge in Changsha

Application of UHPC in China - Grout for Anchor

矮寨大桥 Aizhai Bridge: CFRP Anchor + RPC Grout





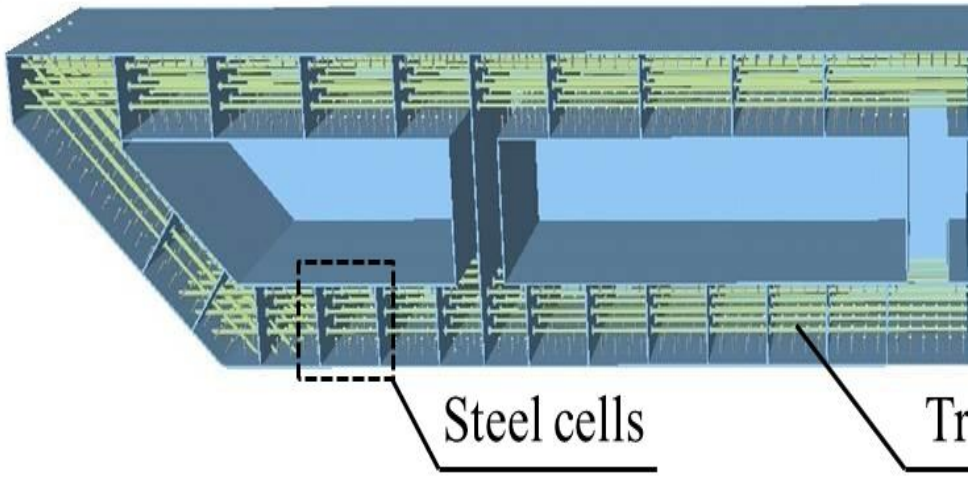
Applications of UHPC in China

- 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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