Recent Development and Application of Low Carbon LC³ Concrete

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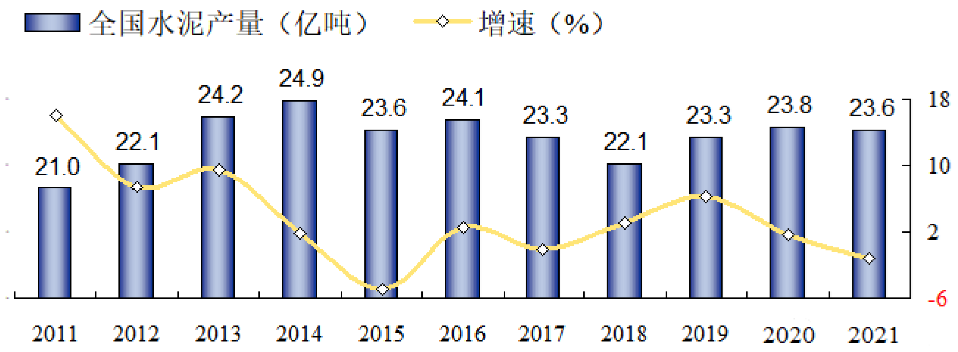
Outline

01 Introduction

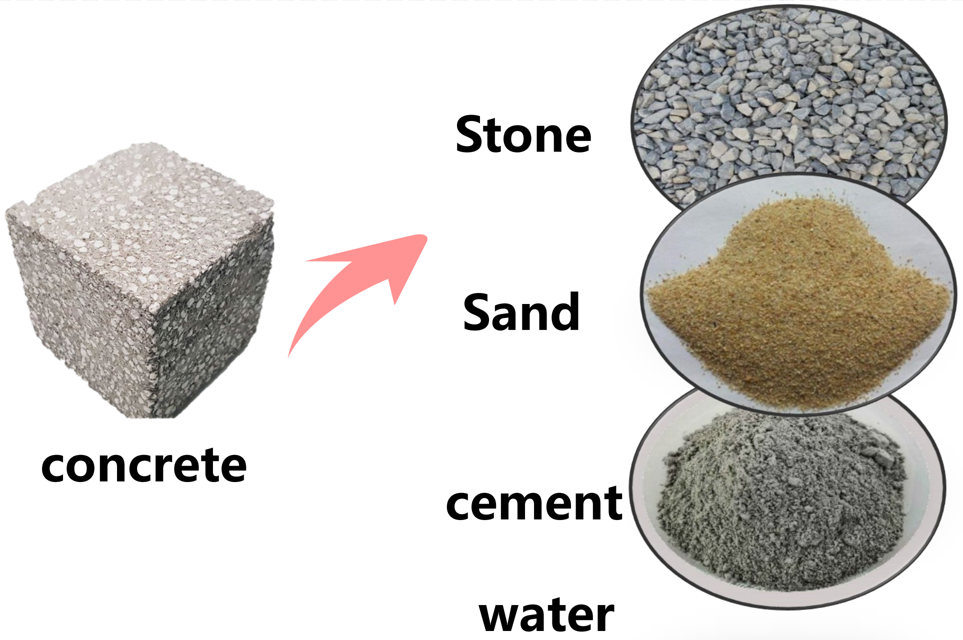
Challenge：Resource depletion and environmental damage

- China's construction industry consumes 2 billion tons of cement a year, accounting for 13% of its carbon emissions

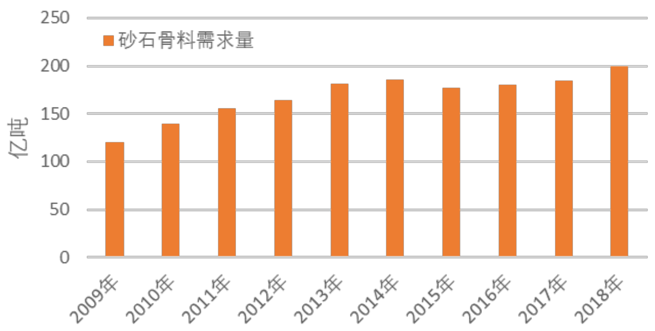


建材行业中水泥年产量超20亿吨

Cement production beyond 2 billion tones



- China's annual aggregate consumption of up to 20 billion tons of sand & stone



China has approximately 840 hectares of mountainous land at an elevation of 500 meters are leveled each year.

Carbon Peak by 2030 and Carbon Neutralization by 2060 (CPCN)

- Global cement grows by 3% annually;
- Low-carbon supplementary cementitious materials (SCMs) and environmentally friendly cement.

Wei J, Cen K, Geng Y. Evaluation and mitigation of cement CO_2 emissions: projection of emission scenarios toward 2030 in China and proposal of the roadmap to a low-carbon world by 2050[J]. Mitigation and Adaptation Strategies for Global Change, 2019,24(2):301-328. Karen Scrivener, Fernando Martriren, Shashank Bishnoi, Soumen Maity. Calcined clay limestone cements (LC3). Cement Concrete Res,114:49-56 (2018).

01 Introduction

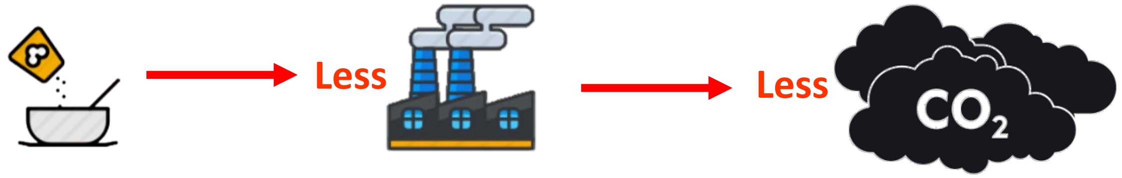
Opportunities: Low-Carbon Cement and Waste Utilization

Low carbon solution: Limestone Calcined Clay Cement, LC^3

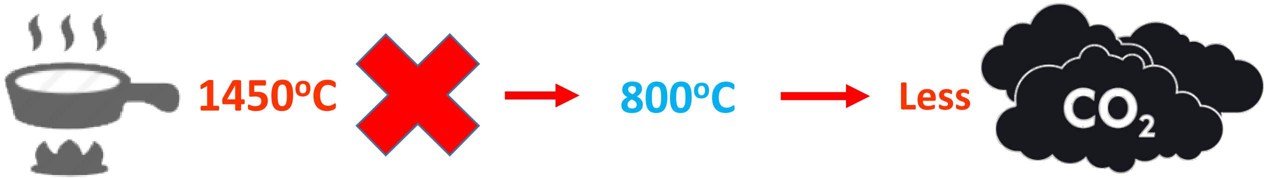
Emissions of LC^3 are estimated to be 20-30% lower than OPC:

- **Reduced clinker content** leads to less process emissions from the decarbonation of limestone and less emissions from heating limestone to form clinker;

- **Grinding limestone** takes less energy than heating it;



- **Calcination of clay** takes place at 800°C and uses roughly 55% of the energy needed for clinkerisation at 1450°C.



Green aggregates：artificial aggregate by waste utilization

- China annually produces ~2 billion tons of construction waste
- Recycling and reuse save ~700 billion and conserve 530 million tons of standard coal, reduces 1.39 billion tons CO2 emissions
- Light aggregate products such as shale ceramsite, fly ash ceramsite, sludge ceramsite, and clay ceramsite
- "3060 CPCN Goals"：China is vigorously promoting environmentally friendly waste utilization, prefabricated construction, and green energy-saving buildings...

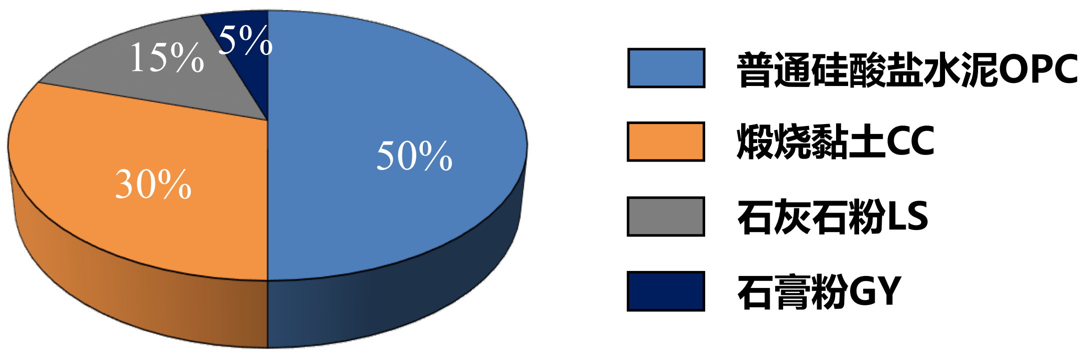
Company: Henan Baichy Machinery Equipment Co.,Ltd

Scrivener K, Martirena F, Bishnoi S, et al. Calcined clay limestone cements (LC3). Cement and Concrete Research, 2018, 114:49-56.

01

Introduction

Limestone + Calcined Clay + Cement = LC^3



Motivation

- Raw materials for calcined clay, such as low-quality tailings or waste clay (other solid waste), are available
- Hydration mechanism, physical and chemical properties, short-term mechanical properties, mix design, and durability
- Structural performance of LC^3-RC members is not well understood

Outline

1. Introduction

2. Development of LC^3 concrete based on local resources

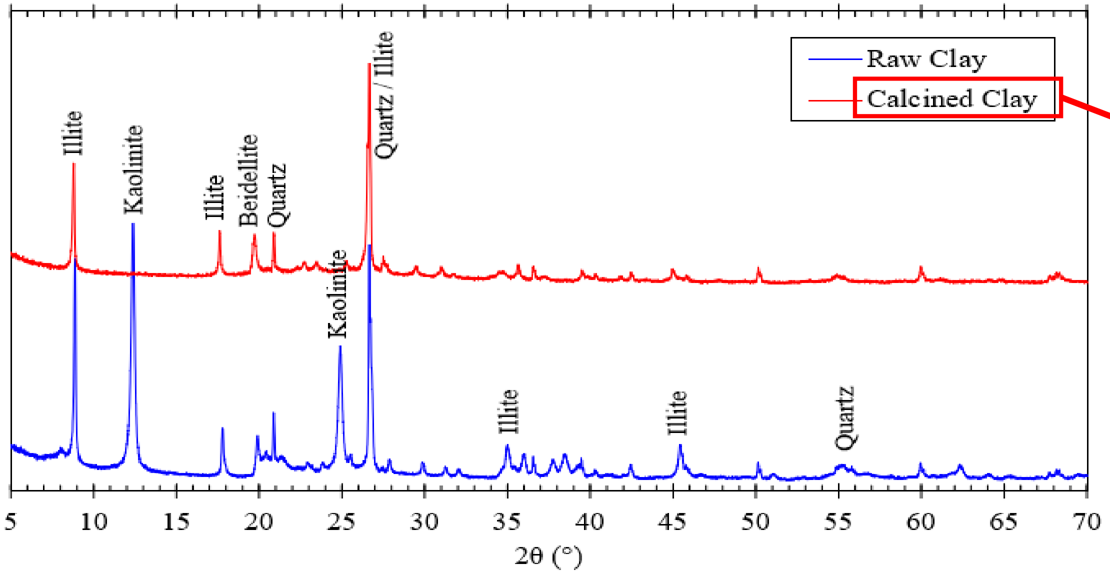
3. Structural behavior of reinforced LC^3 concrete members

4. Durability performance of LC^3-based ULCC against chloride ingression and carbonation

5. Development and application of LC^3 based lightweight core-shell aggregate concrete

6. Conclusions

02 Development of LC^3 concrete based on local resources



Calcined clay**煅烧黏土**（广东茂名）

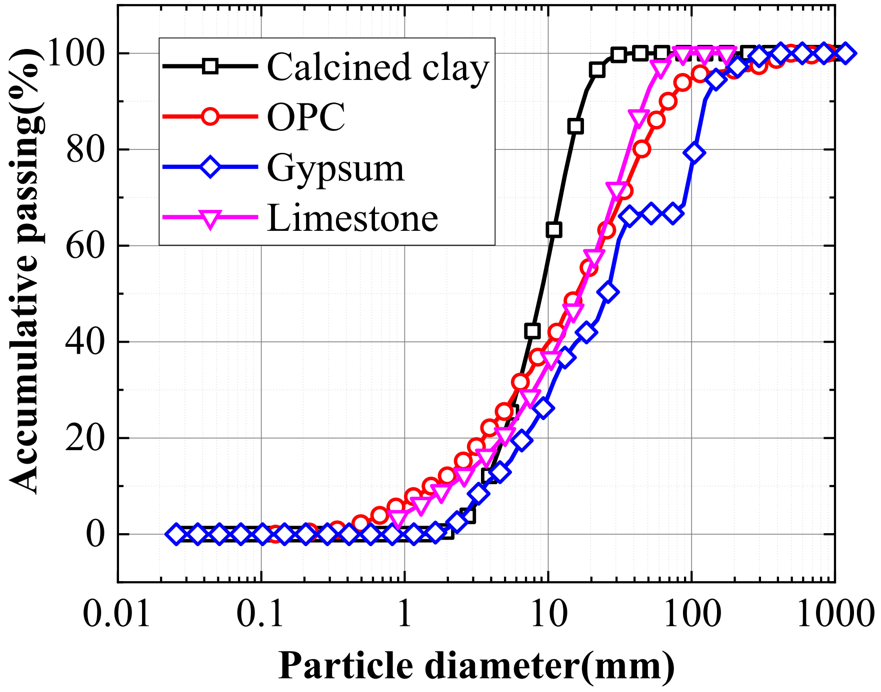
"Kaolin + Tailing" Comprehensive Utilization

"高岭土+尾矿综合利用"模式

The kaolin reserves in Maoming, Guangdong are abundant and of high quality, accounting for **80%** of kaolin used in papermaking in China.

Chemical composition of each constituent in LC^3

Oxides	Calcined Clay (%)	Gypsum(%)	Limestone(%)	clinker(%)
SiO_2	52.70	3.09	0.30	22.37
Al_2O_3	36.90	1.34	0.10	4.36
K2O	3.49	0.05	-	-
Fe_2O_3	1.99	0.36	0.08	3.38
MgO	0.28	1.31	0.64	2.43
TiO_2	0.18	-	-	-
SO_3	0.12	40.87	-	2.45
CaO	0.04	30.51	81.13	61.08
Rb_2O	0.03	-	-	-
SrO	-	-	0.02	-
Others	4.27	23.26	17.73	2.71



02 Development of LC^3 concrete based on local resources

Binder system compositions

Binder	OPC	Calcined Clay	Limestone	Gypsum	Water
LC^3	52.3	30	15	2.7	50
OPC	100.0	-	-	-	50

Mix proportion of mortar and concrete

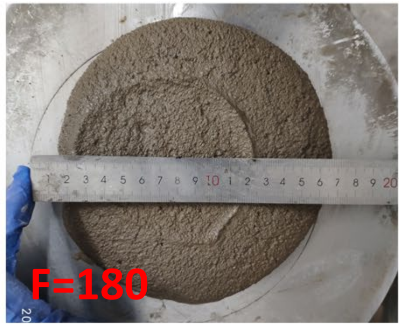
Mixture No.	W/B	Binder proportion				Proportion			Slump/flow (mm)	Remark
		OPC	CC	LS	GYP	Sand	CAgg	SP		
OPM-0.50	0.50	1.000	–	–	–	3.00	–	–	230	OPC mortar
OPM-0.45	0.45	1.000	–	–	–	3.00	–	–	200	
OPM-0.40	0.40	1.000	–	–	–	3.00	–	0.0027	190	
OPM-0.35	0.35	1.000	–	–	–	3.00	–	0.0047	185	
LCM-0.50	0.50	0.523	0.300	0.150	0.027	3.00	–	0.0037	220	LC^3 mortar
LCM-0.45	0.45	0.523	0.300	0.150	0.027	3.00	–	0.0052	200	
LCM-0.40	0.40	0.523	0.300	0.150	0.027	3.00	–	0.0073	180	
LCM-0.35	0.35	0.523	0.300	0.150	0.027	3.00	–	0.0115	180	
OC-0.50	0.50	1.000	–	–	–	1.43	2.21	–	190	OPC concrete
OC-0.40	0.40	1.000	–	–	–	1.43	2.21	0.0032	70	
LCC-0.50	0.50	0.523	0.300	0.150	0.027	1.43	2.21	0.0032	175	LC^3 concrete
LCC-0.40	0.40	0.523	0.300	0.150	0.027	1.43	2.21	0.0057	90	

Workability

(a) OPM-0.50

(b) LCM-0.50

(c) OPM-0.35



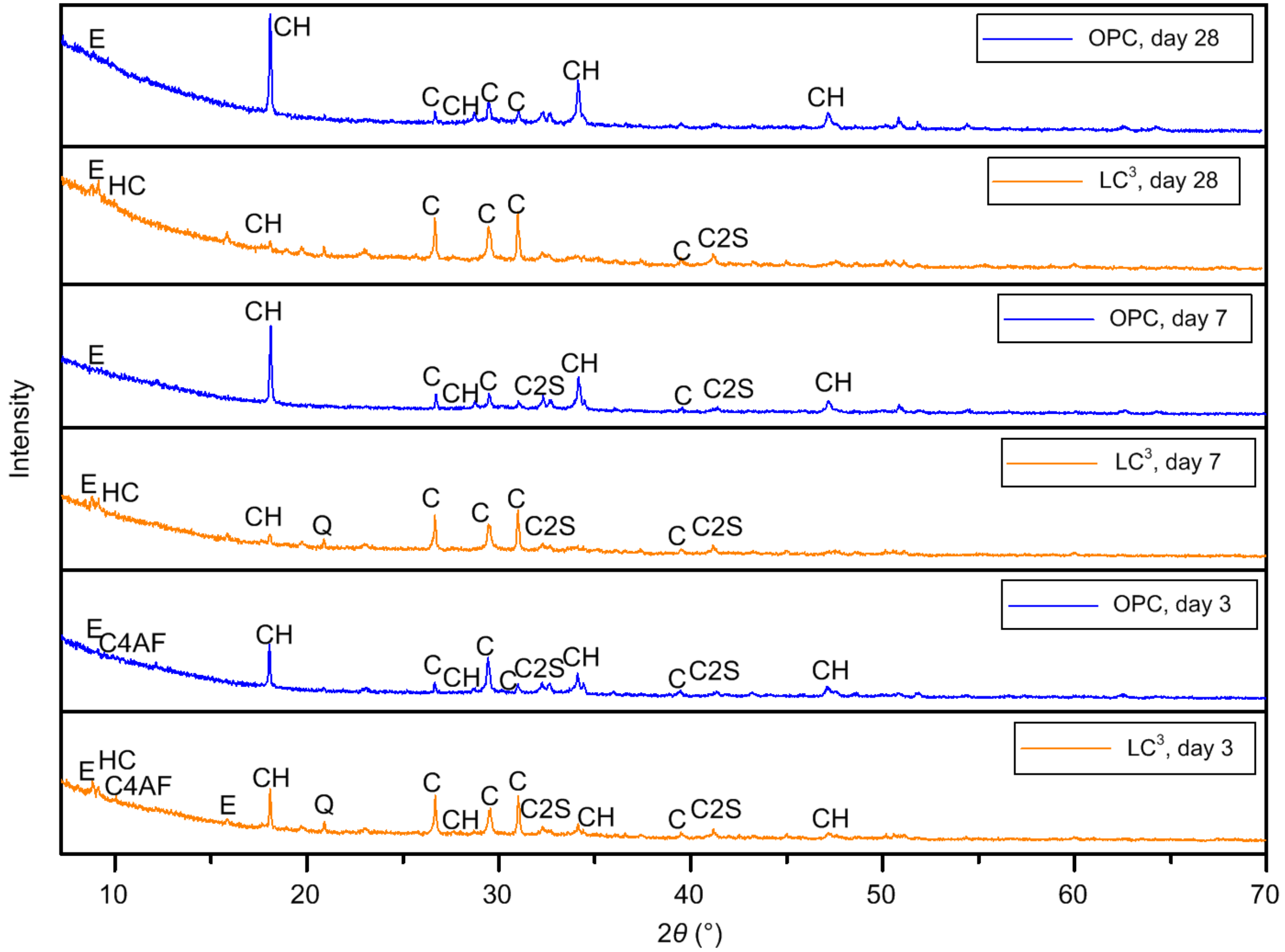
(d) LCM-0.35

(e) OC-0.50

(f) LCC-0.50

02 Development of LC^3 concrete based on local resources

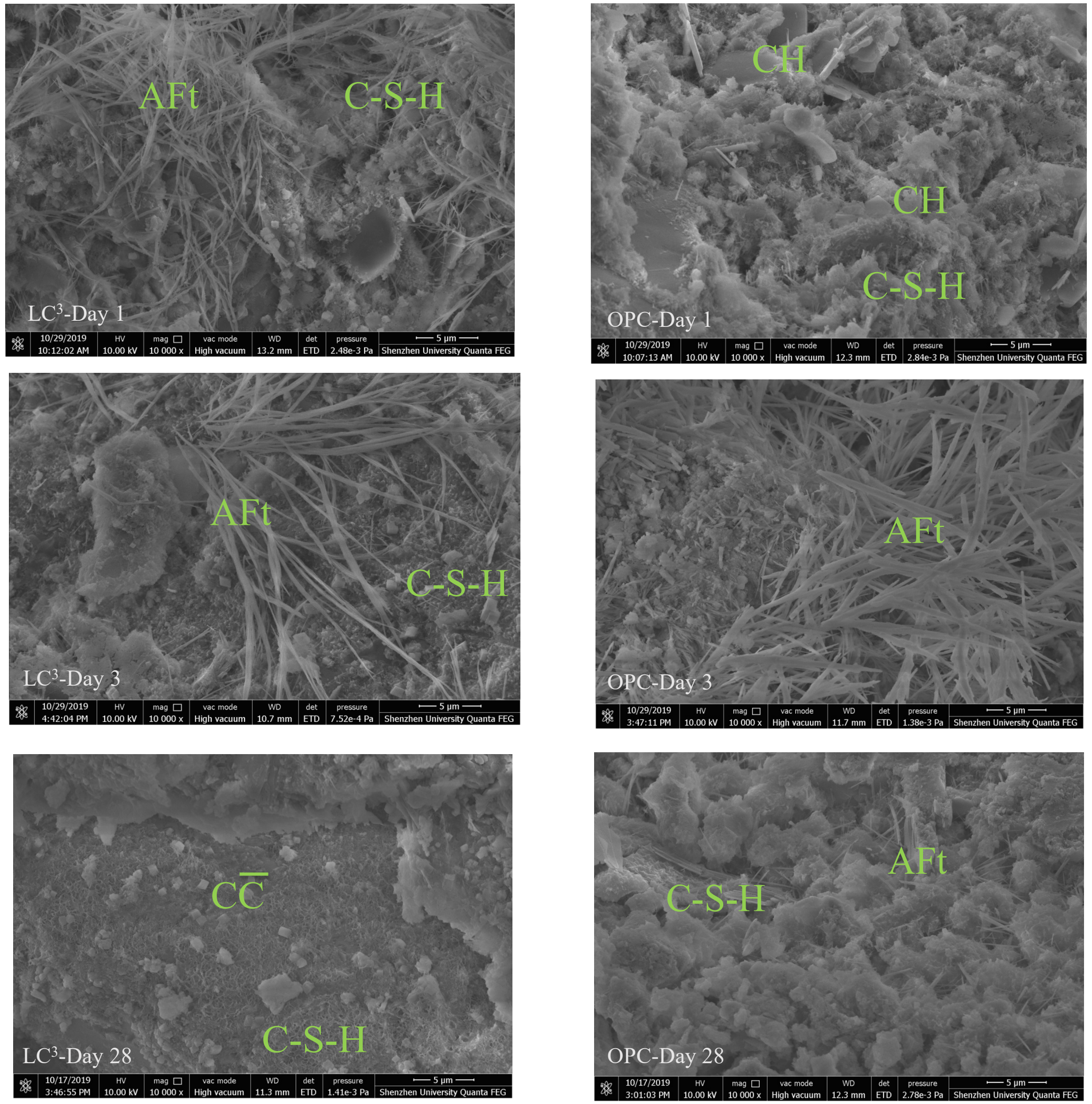
XRD plots of OPC and LC^3 pastes with different curing ages



Second hydration

$$\begin{cases} S + CH \rightarrow C\text{-}S\text{-}H, \\ A_{(\text{from calcined clay})} + C\overline{C} + 3CH \rightarrow C_3A \cdot C\overline{C} \cdot H_{11}, \end{cases}$$

S represents amorphous silica from calcined clay, A represents alumina, C3A represents tricalcium aluminate, and CC represents CaCO3.



SEM images of OPC and LC^3 pastes under different curing ages

Huang et al. / J Zhejiang Univ-Sci A (Appl Phys & Eng) 2020 21(11):892-907

02 Development of LC³ concrete based on local resources

Mechanical properties

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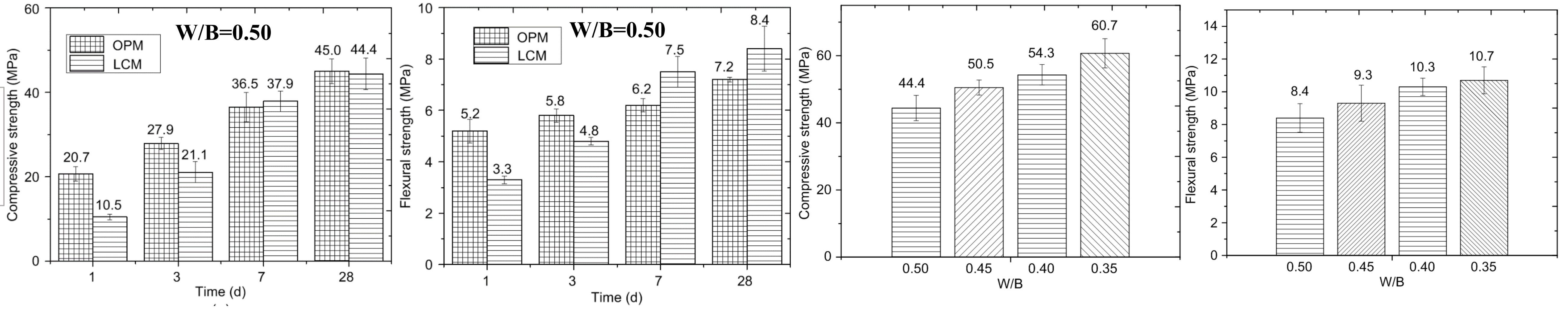

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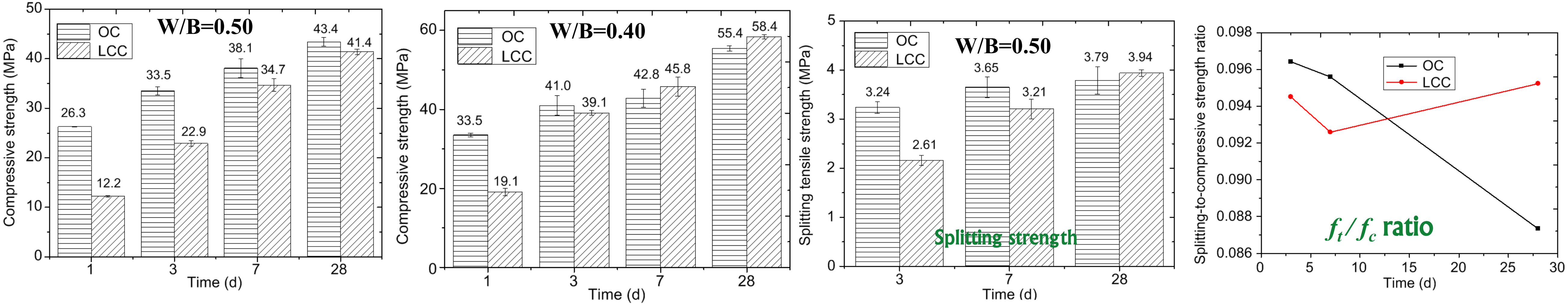
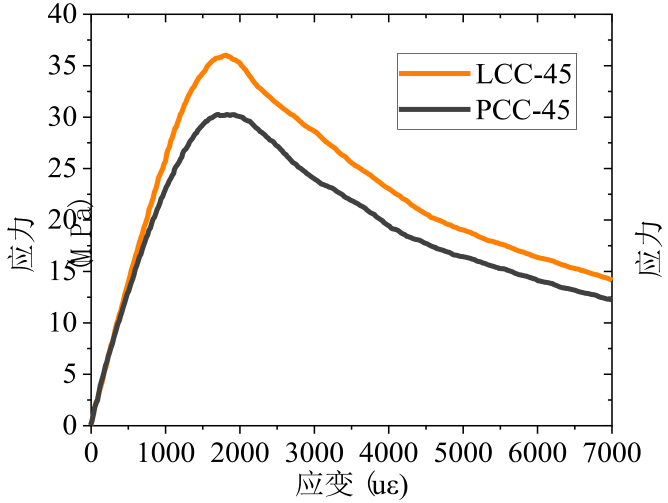


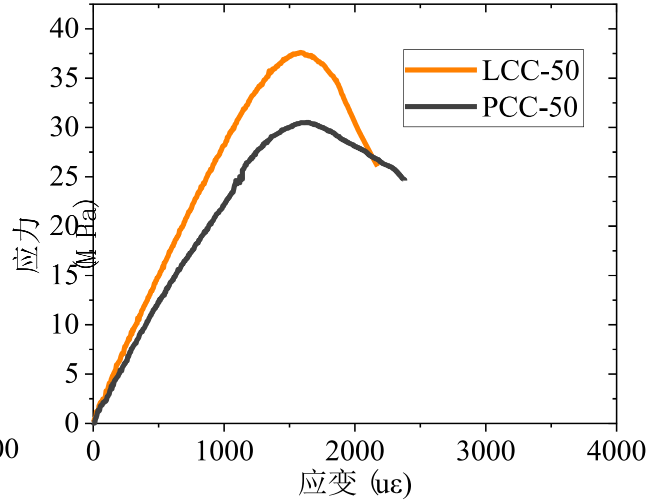
- ➢ LC³ mortar: 1-3day lower early strength; 7 day strength catch up to OPC, 28day comparable strength;
- ➢ LC³ concrete: higher splitting-compressive strength ratio(折压比), indicating a higher toughness.

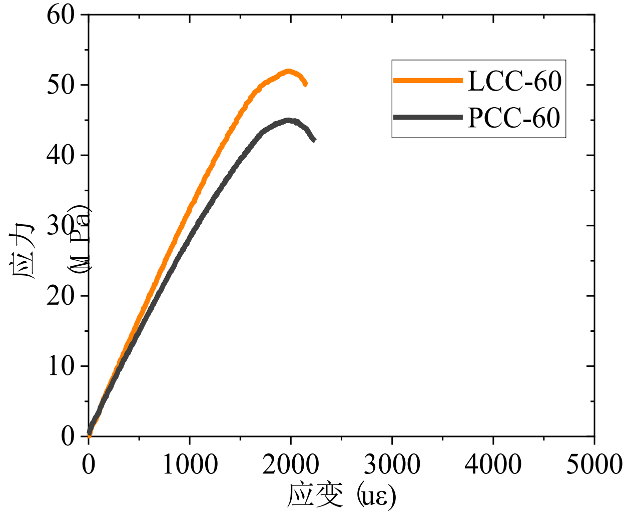
02 Development of LC^3 concrete based on local resources

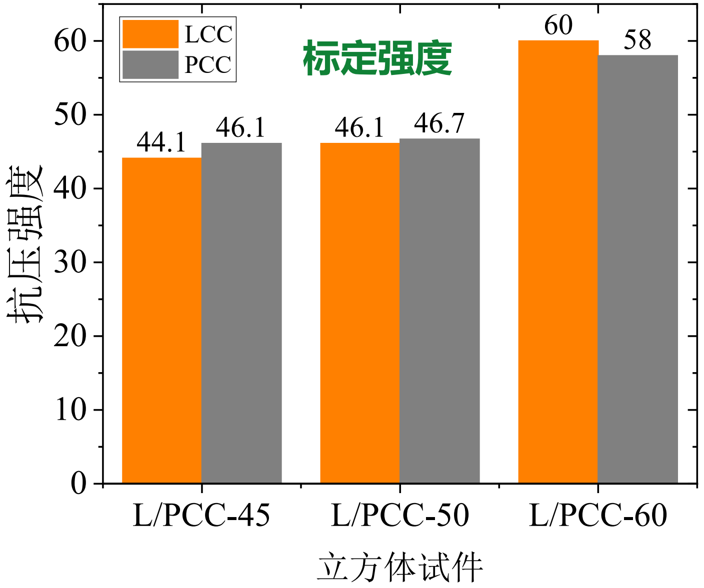
Compression test

LC^3 OPC









Elastic modulus (GPa)

Type	L/PCC-45	L/PCC-50	L/PCC-60
LCC	27	30	32
PCC	26	24	29

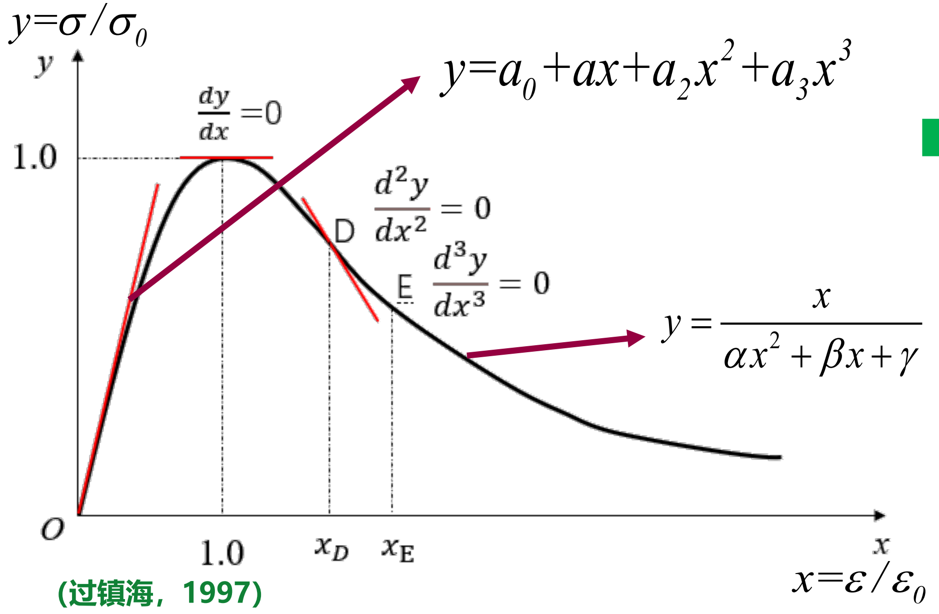
Ultimate strain

Type	L/PCC-45	L/PCC-50	L/PCC-60
LCC	1801×10^{-6}	1582×10^{-6}	1990×10^{-6}
PCC	1710×10^{-6}	1640×10^{-6}	1970×10^{-6}

- **Similar failure mode, stress-strain curve and ultimate strain;**
- **Higher elastic modulus due to denser microstructure.**

02 Development of LC³ concrete based on local resources

Constitutive model for LC3 concrete



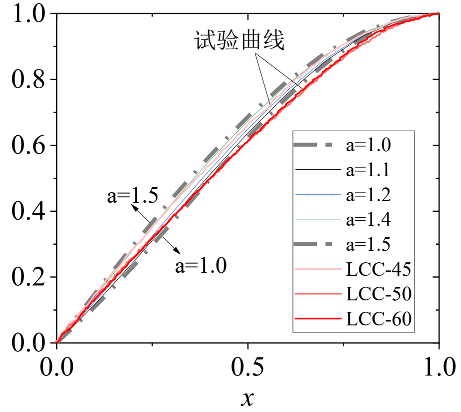
(过镇海，1997)

$$y=a_0+ax+a_2x^2+a_3x^3$$

$x=0$	$y=0$
$x=1$	$y=1$
$x=1$	$\frac{dy}{dx}=0$

$$y=ax+(3-2a)x^2+(a-2)x^3$$

独立参数*a*

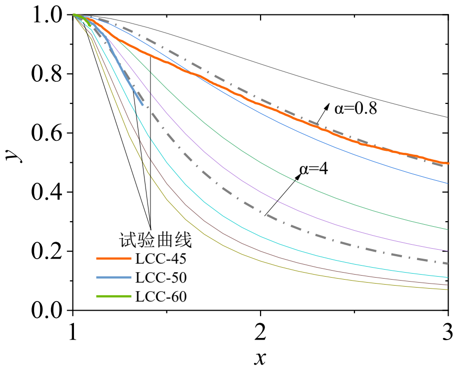


$$y=\frac{x}{\alpha x^2+\beta x+\gamma}$$

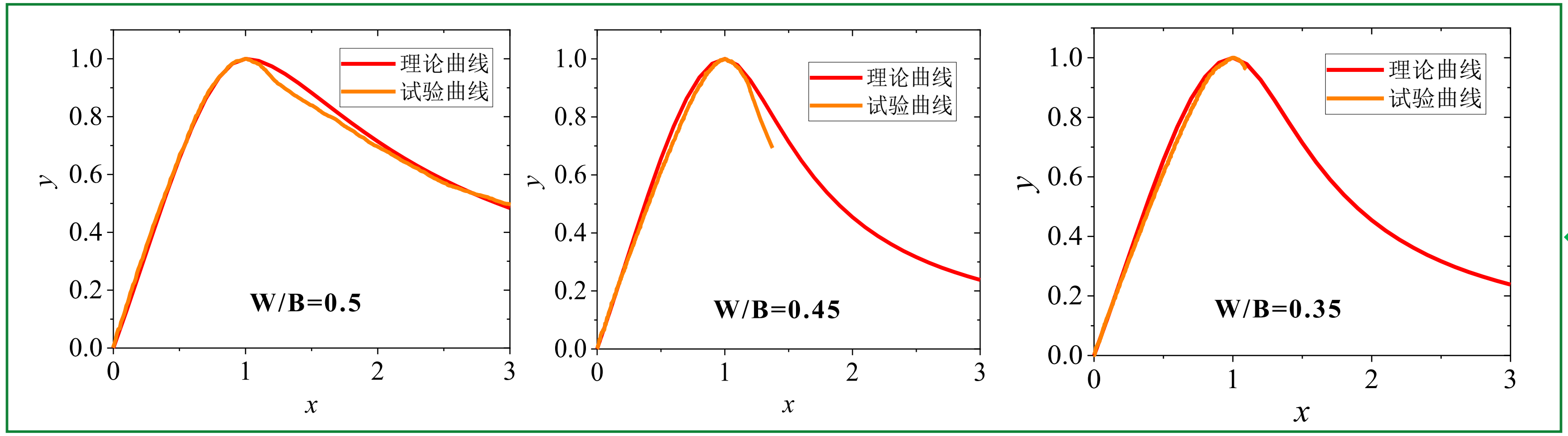
$x=1$	$y=1$
$x=1$	$\frac{dy}{dx}=0$

$$y=\frac{x}{\alpha(x-1)^2+x}$$

独立参数*α*



$$y=\begin{cases} ax+(3-2a)x^2+(a-2)x^3, & 0\le x\le 1, 1\le a\le 1.5 \\ \frac{x}{\alpha(x-1)^2+x}, & 1< x, 0.8\le a\le 4 \end{cases}$$



➢ **Typical concrete constitutive model is applicable to LC³ concrete.**

Outline

03 Structural behavior of reinforced LC³ concrete members

- 3.1 Bond behavior between reinforced bar and LC³ concrete
- 3.2 Flexural & shear behavior of reinforced LC³ concrete beams
- 3.3 Code predictions and assessments of flexural and shear resistance

3.1 Bond behavior between reinforced bar and LC^3 concrete

Pull-out test program

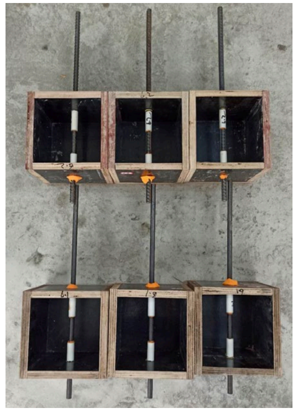
Normal concrete

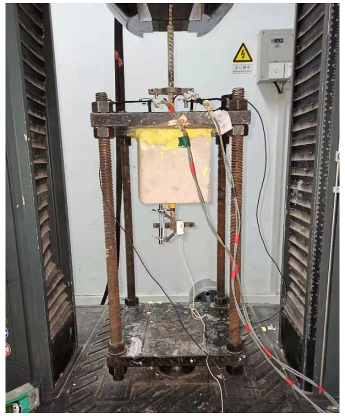
	f_{cu}(MPa)	d(mm)	S(mm)	l_d(mm)
PCC-12D	45	12	150	60
LCC-12D	45	12	150	60
LCC-16D	45	16	150	60
LCC-18D	45	18	150	60
LCC-20D	45	20	150	60
LCC-50L	45	12	150	50
LCC-60L	45	12	150	60
LCC-100L	45	12	150	100
LCC-45	45	12	150	60
LCC-50	50	12	150	60
LCC-60	60	12	150	60
LCC-110S	45	12	110	60
LCC-150S	45	12	150	60
LCC-200S	45	12	200	60

Rebar diameter   Bond length   Concrete strength   Concrete cover

Mix proportions (kg/m^3)

Mixture	Concrete Grade	W/B	OPC	Calcined Clay	Limestone	Gypsum	Coarse aggregate	Sand
LCC-45	C45	0.5	255	146.4	73.2	13.2	1080	700
LCC-50	C50	0.45	255	146.4	73.2	13.2	1080	700
LCC-60	C60	0.35	255	146.4	73.2	13.2	1080	700
PCC-45	C45	0.55	488	-	-	-	1080	700
PCC-50	C50	0.5	488	-	-	-	1080	700
PCC-60	C60	0.4	488	-	-	-	1080	700

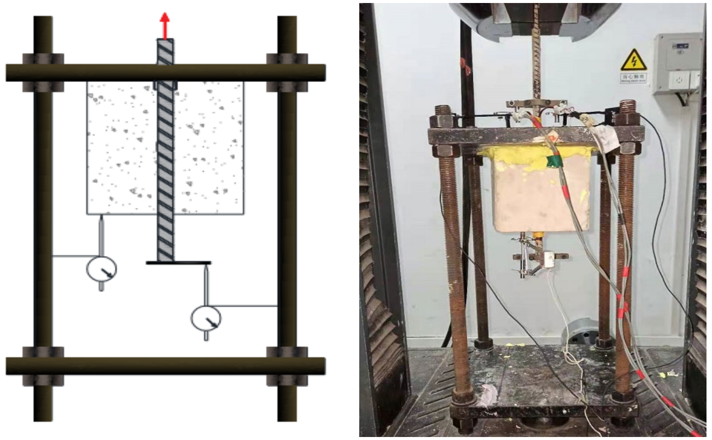




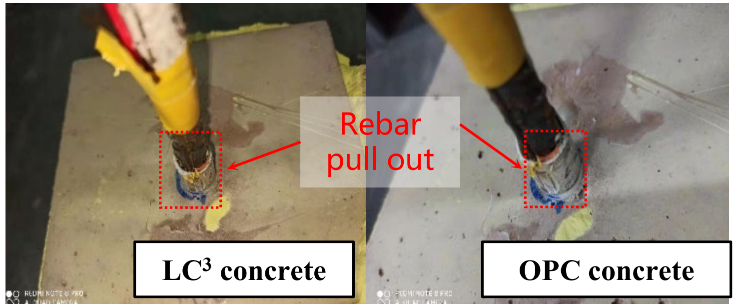
- Mix proportion design to obtain similar compressive strength: **C45**, **C50** and **C60;**
- Concrete cylinders: **D150mm ×300mm;**
- Pull out tests: **36 specimens.**

3.1 Bond behavior between reinforced bar and LC³ concrete

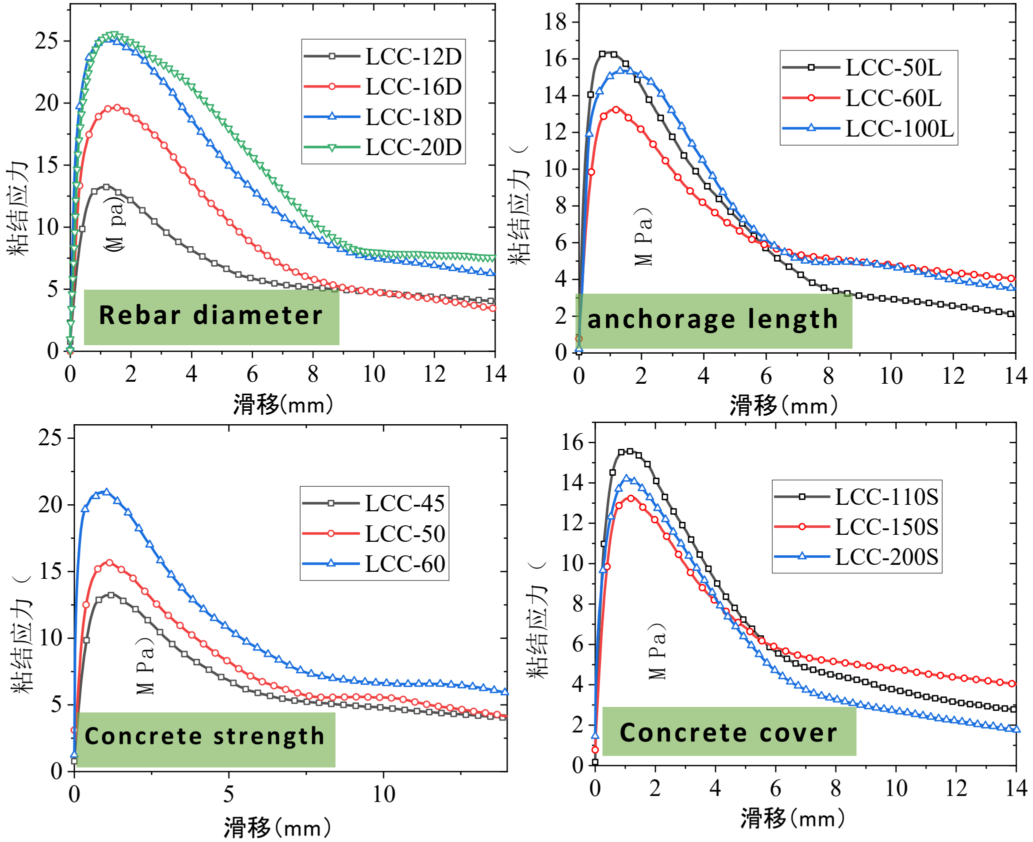
(1)Bond-slip behavior between LC³ concrete and rebar：bond failure mechanism, bond-slip curve, key parameters



Pull out test setup



Failure mode



Parametric study

- Bond strength increases with larger bar diameter
- Higher concrete strength induces to higher bond strength
- Little impact on bond slip behavior from concrete cover

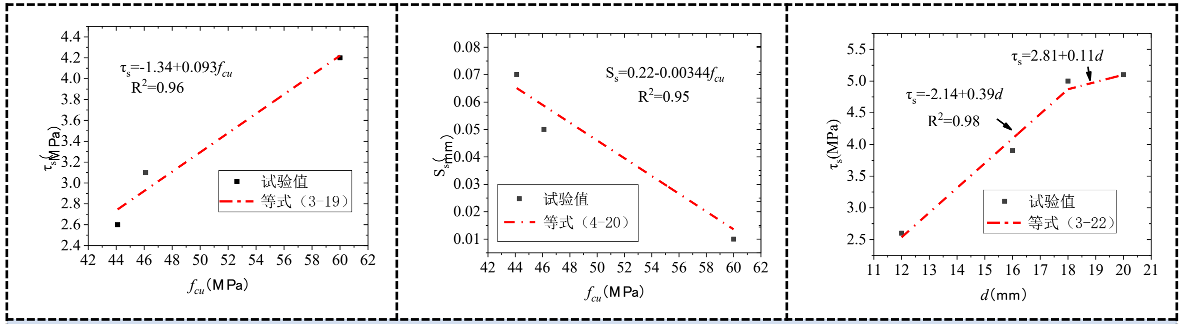
Bond-slip behavior between LC³ concrete and rebar is essentially consistent with that of OPC concrete and rebar.

3.1 Bond behavior between reinforced bar and LC³ concrete

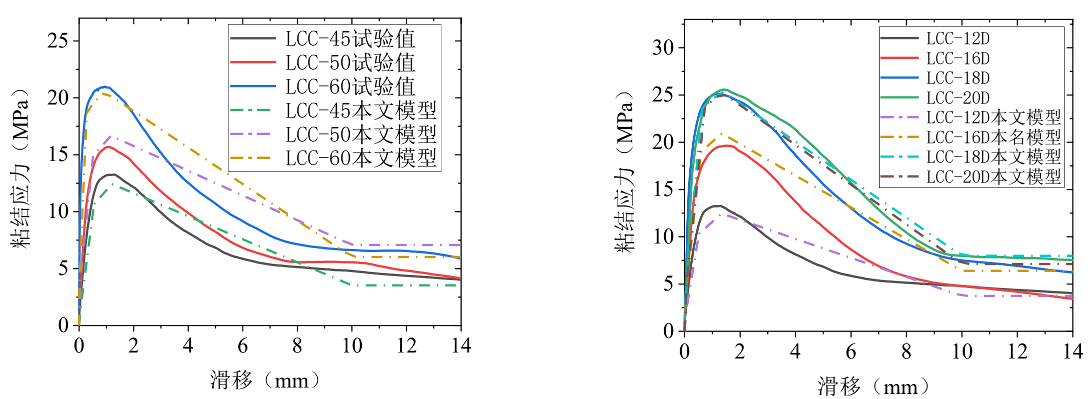
(2) Bond-slip behavior between LC³ concrete and rebar ： propose modified bond-slip constitutive model

$$\tau=\begin{cases}K_1S, & S\le S_s\\ \tau_s+K_2\left(S\text{-}S_s\right), & S_s\le S\le S_{cr}\\ \tau_{cr}+K_3\left(S\text{-}S_{cr}\right), & S_{cr}\le S\le S_u\\ \tau_{max}+K_4\left(S-S_u\right), & S_u\le S\le S_r\\ \tau_r, & S\ge S_r\end{cases}$$

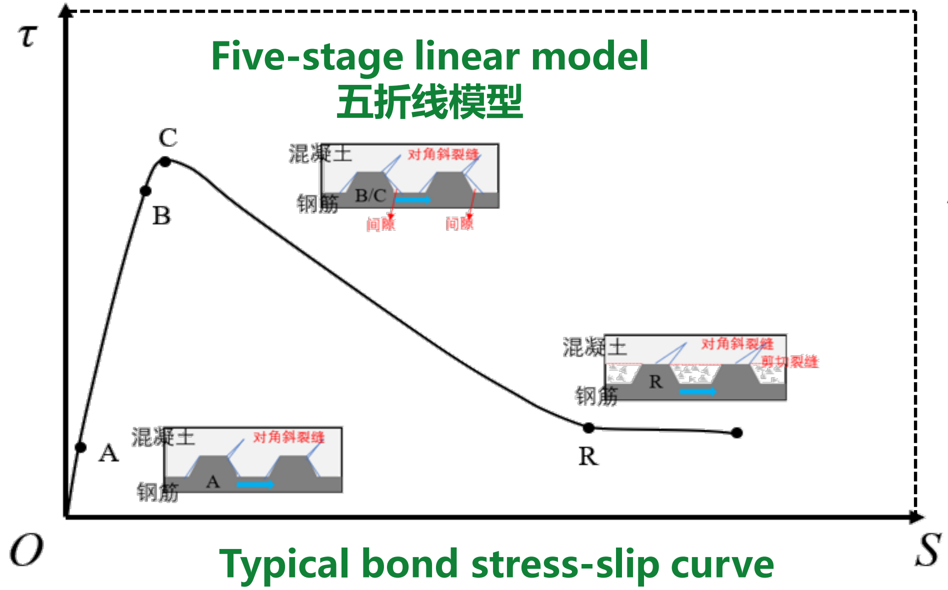
The key parameters: **concrete strength** and **diameter of rebar**



Linear fitting (based on pull-out test data)



Test verification



Typical bond stress-slip curve

OA: **Elastic stage;**

AB: **Slip stage;**

BC: **Splitting stage;**

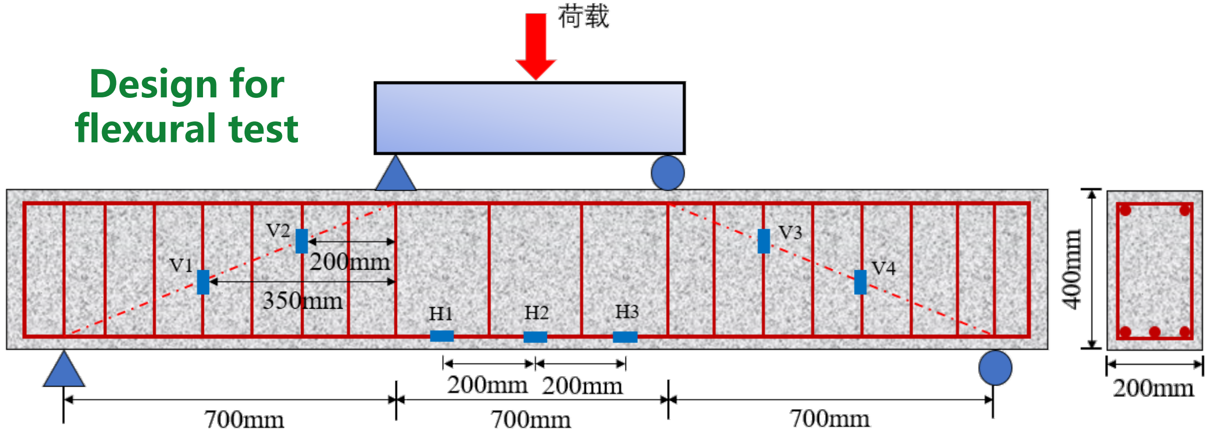
CR: **Descending stage;**

after R: **Residual stress stage**

3.2 Flexural behavior of reinforced LC³ concrete beam

(1) Reveal the failure mechanism under bending, and quantify the impact of concrete type, strength, and reinforcement ratio

Design for flexural test

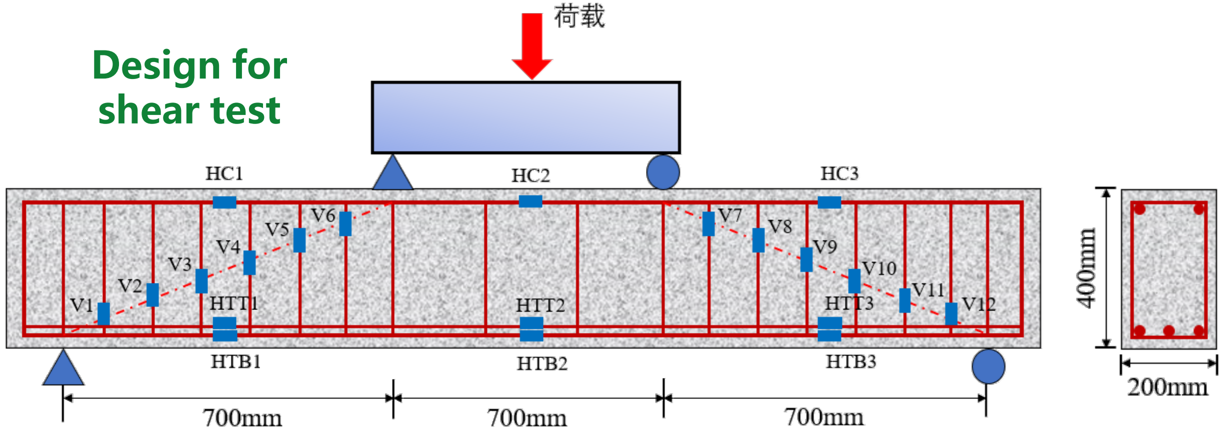


Parameters for flexural test 抗弯试验梁参数(10 full scaled beams)

梁编号	f_c/MPa	ρ%	s/mm	l_0/mm	b/mm	h/mm	f_{cu}/MPa
L/PCC-45-L	45	1.07	80	2100	200	400	46/47
L/PCC-45-M	45	1.60	80	2100	200	400	46/47
L/PCC-45-H	45	2.32	50	2100	200	400	46/47
L/PCC-50-M	50	1.60	80	2100	200	400	52/55
L/PCC-60-M	60	1.60	80	2100	200	400	58/61

混凝土类型　混凝土强度　配筋率

Design for shear test



Parameters of shear test 抗剪试验梁参数(14 full scaled beams)

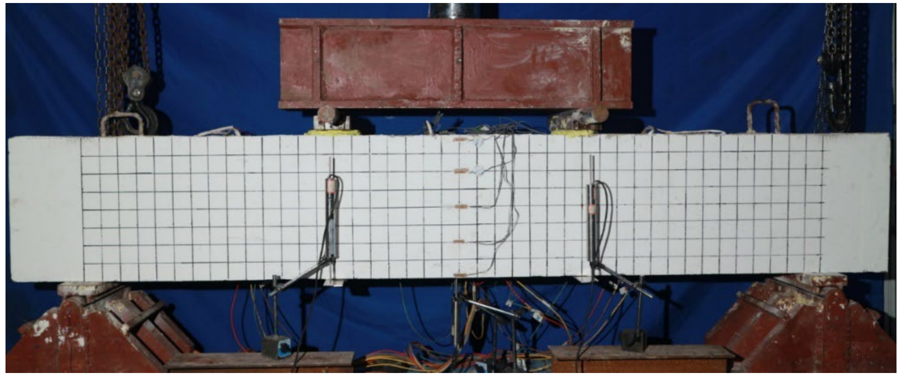
梁编号	f_c/MPa	ρ%	λ	s/mm	l_0/mm	b/mm	h/mm	f_{cu}/mm
L/PCC-45-M-1.5	45	3.67	1.5	150	2100	200	400	46/47
L/PCC-45-M-2	45	3.67	2.0	150	2100	200	400	46/47
L/PCC-45-M-2.5	45	3.67	2.5	150	2100	200	400	46/47
L/PCC-45-L-2	45	3.67	2.0	200	2100	200	400	46/47
L/PCC-45-H-2	45	3.67	2.0	100	2100	200	400	46/47
L/PCC-50-M-2	50	3.67	2.0	150	2100	200	400	52/55
L/PCC-60-M-2	60	3.67	2.0	150	2100	200	400	58/61

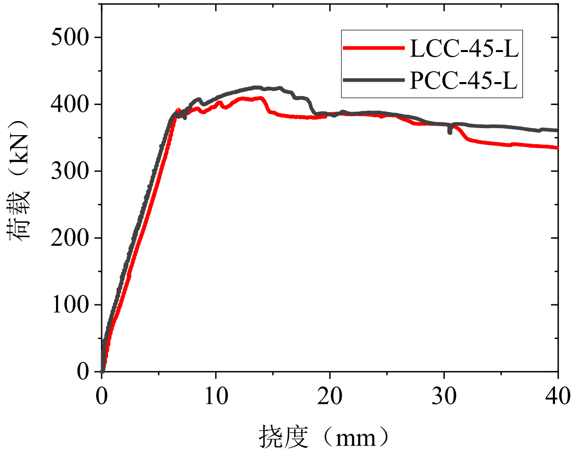
混凝土类型　混凝土强度　配箍率　剪跨比

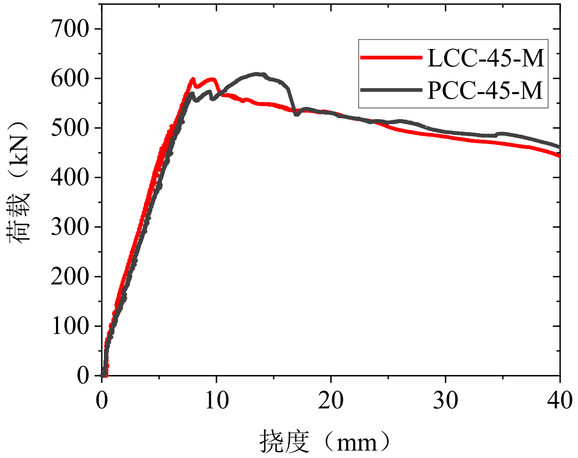
Huang et al. Structural Concrete. 2023;1–23.

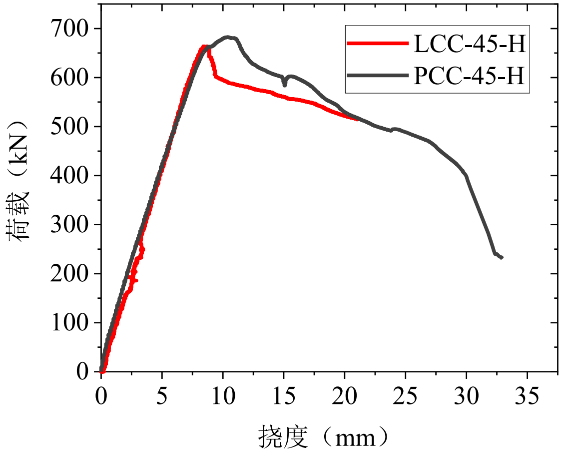
3.2 Flexural behavior of reinforced LC³ concrete beam

(1) Reveal the failure mechanism under bending, and quantify the impact of concrete type, strength, and reinforcement ratio

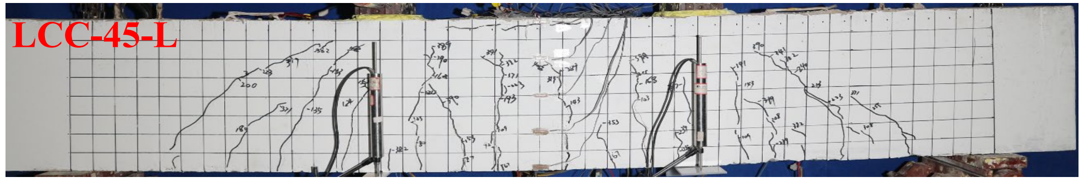


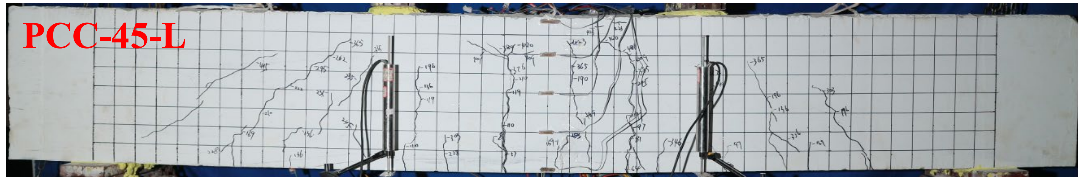


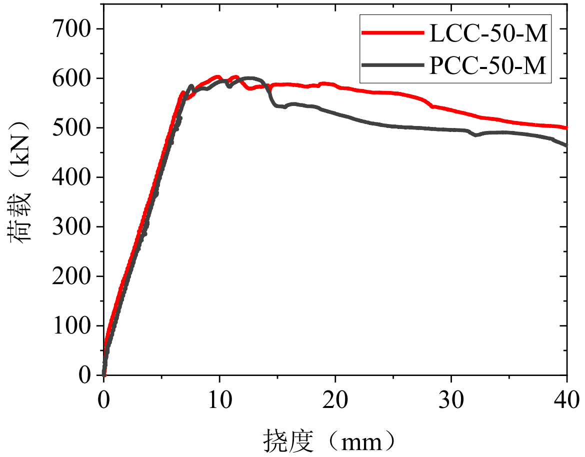


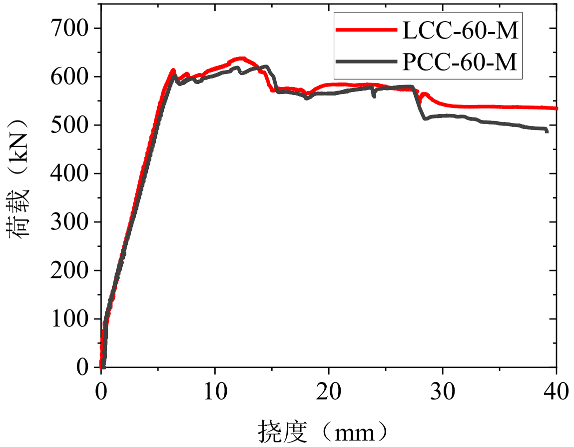


Typical flexural failure: steel bar yielded with vertical cracks







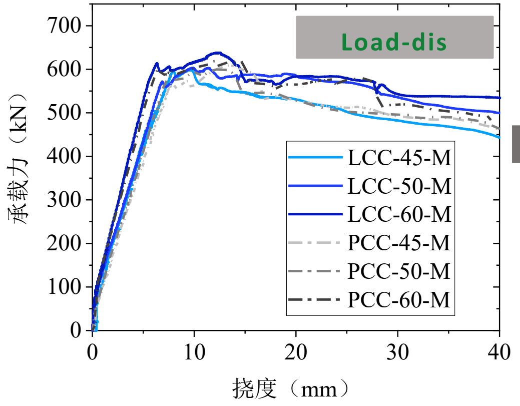


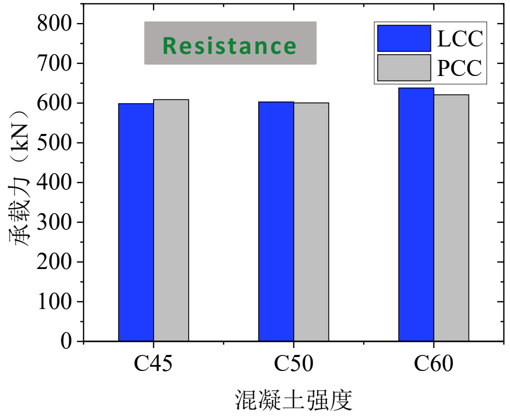
- Similar load-displacement curves and failure mode.
- Comparable stiffness and flexural resistance.

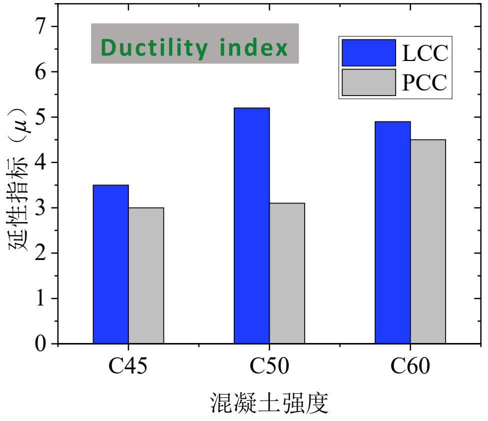
3.2 Flexural behavior of reinforced LC3 concrete beam

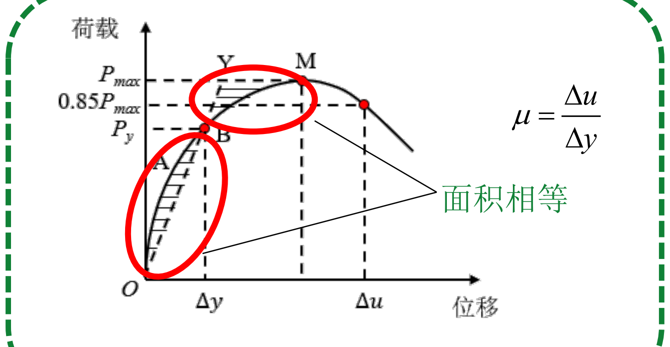
(1) Reveal the failure mechanism under bending, and quantify the impact of concrete type, strength, and reinforcement ratio

Effect of concrete strength



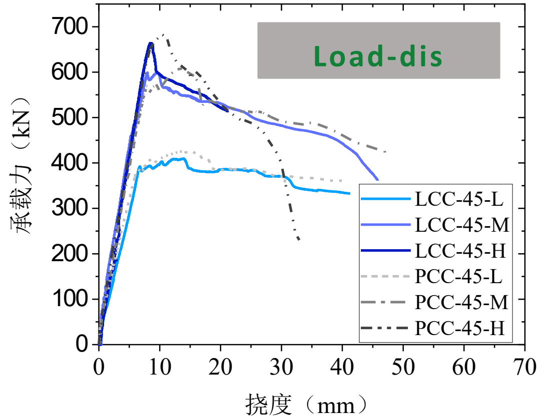


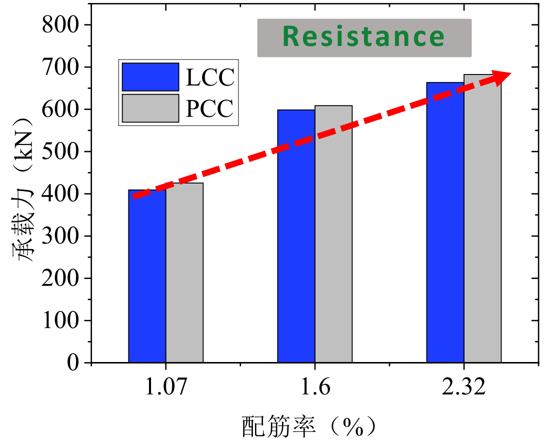


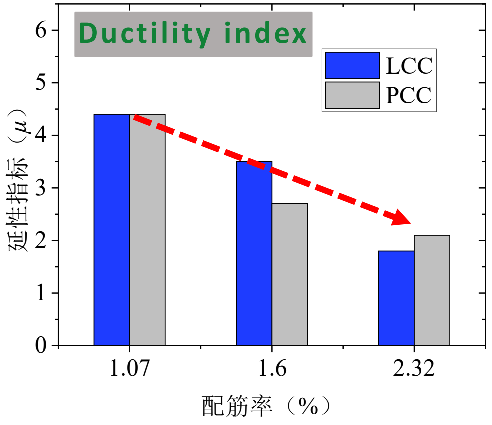


Ductility index

Effect of reinforcement ratio





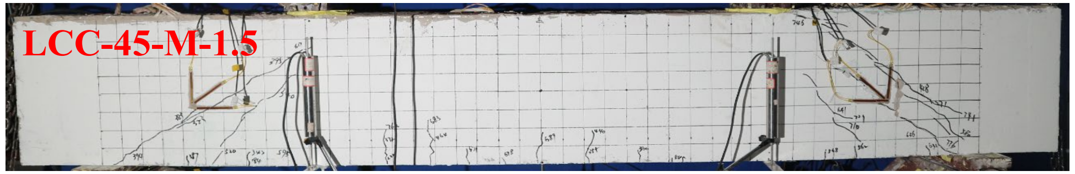


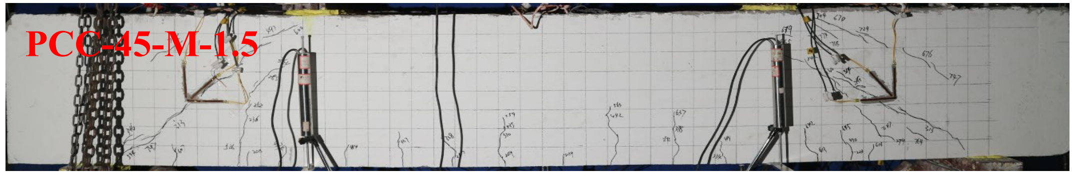
- **Stiffness increases as increasing the strength;**
- **Have similar increasing ratio;**
- **LC^3 beam has higher ductility behavior.**

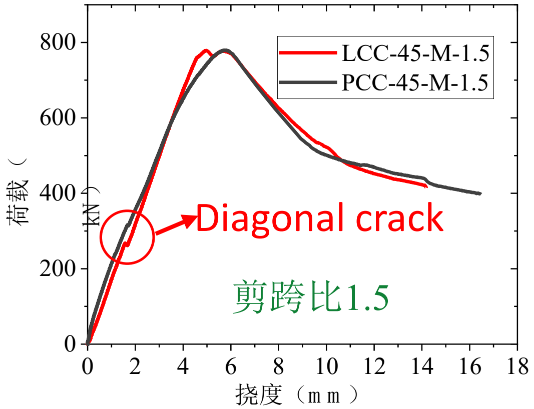
3.2 Flexural behavior of reinforced LC^3 concrete beam

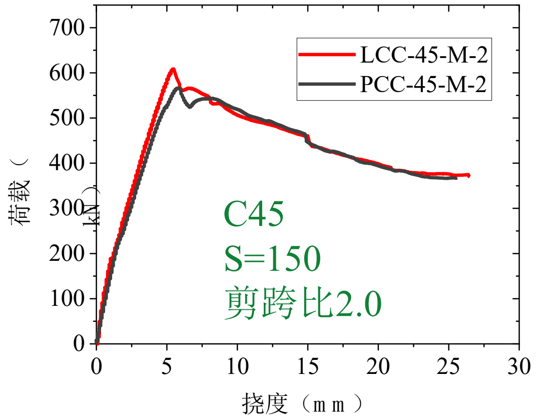
(2) Reveal the failure mechanism under shear, and quantify the impact of concrete type, strength, stirrup ratio and shear-span ratio

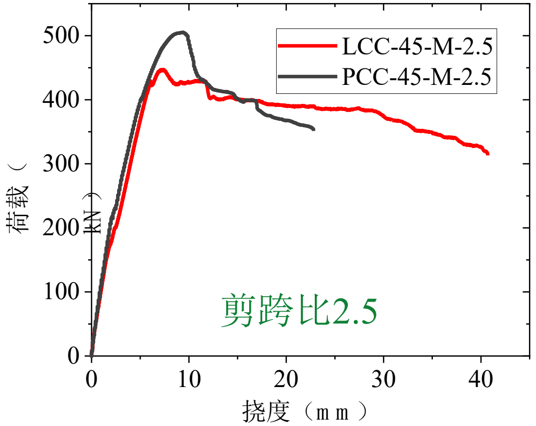
Shear-compression failure: longitudinal bar not yielded with diagonal cracks

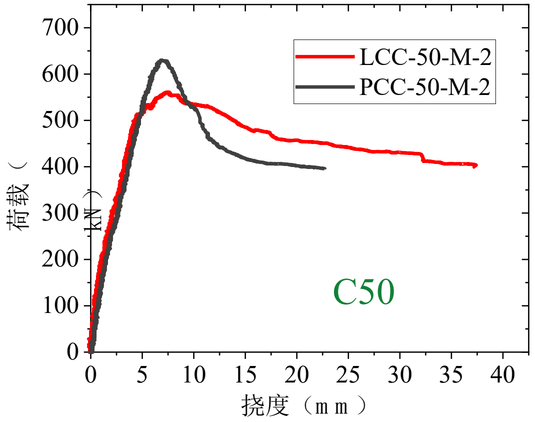


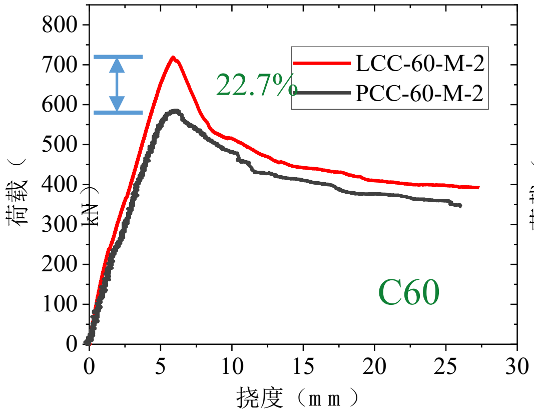


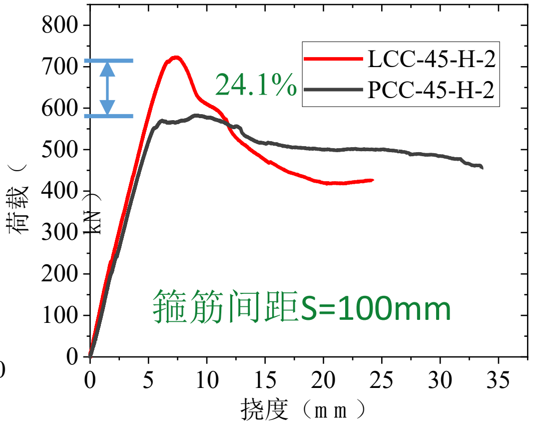


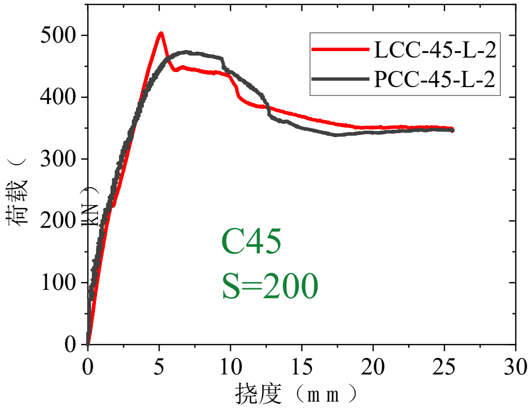










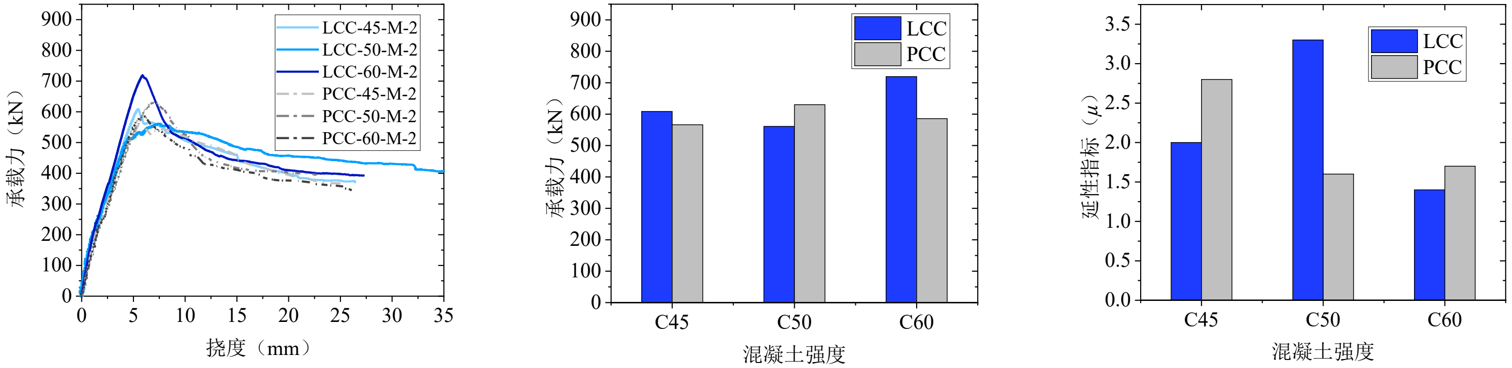


- **Similar load-displacement curves: shear-compression failure; longitudinal bar not yielded,**
- **Higher stirrup ratio and concrete strength group has 24.1% and 22.7% higher shear resistance.**

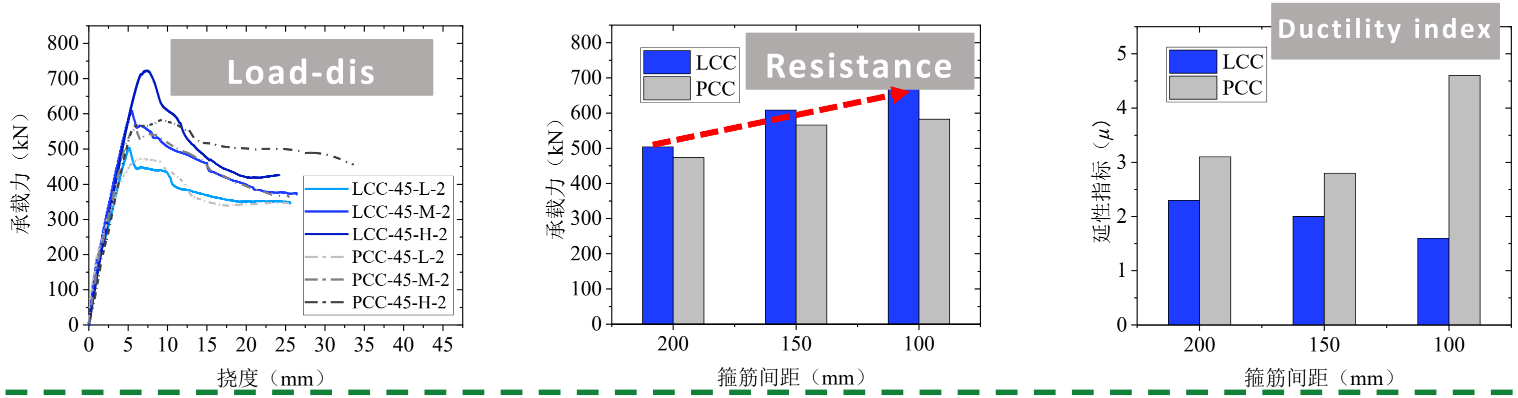
3.2 Flexural behavior of reinforced LC^3 concrete beam

(2) Reveal the failure mechanism under shear, and quantify the impact of concrete type, strength, stirrup ratio and shear span ratio

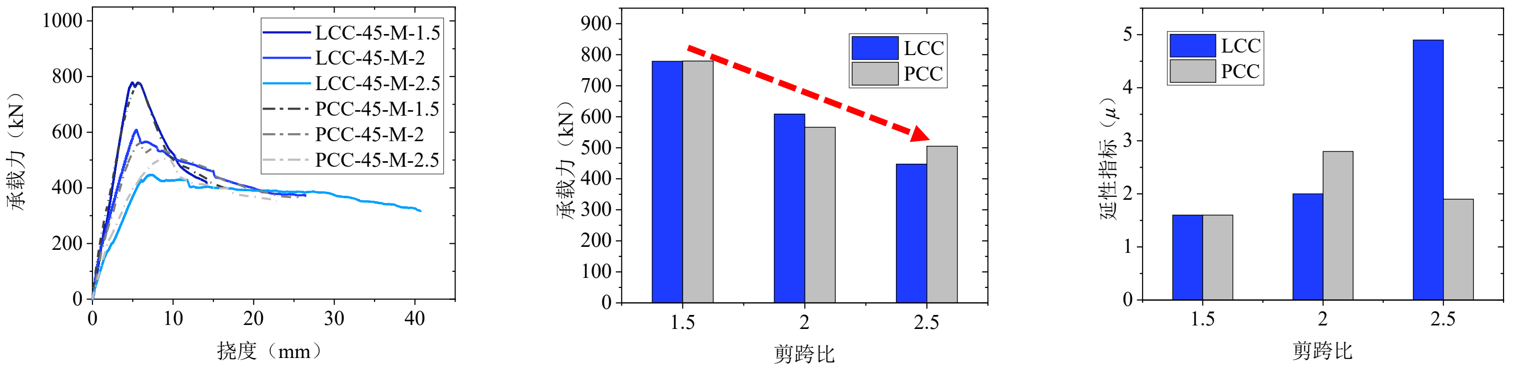
Concrete strength



Stirrup ratio



Shear span ratio



1. Shear-span ratio reduces significantly the shear stiffness;
2. Stirrup ratio and shear span ratio have a more significant impact on the shear resistance.

3.3 Code predictions and assessments of flexural and shear resistance

(1) Prediction and assessment of flexural resistance

Calculation modes in different design codes

Codes	Calculation formulae
GB50010 （中国规范）	$\alpha_1 f_c bx = f_y A_s - f_y' A_s' + f_{py} A_p + (\sigma_{p0}' - \sigma_{py}') A_p'$ $M_u = \alpha_1 f_c bx\left(h_0 - \frac{x}{2}\right) + f_y' A_s'(h_0 - a_s') + f_{py} A_p + (\sigma_{p0}' - \sigma_{py}') A_p'(h_0 - a_p')$
ACI 318 （美国规范）	$A_s f_y = 0.85 f_c' ab + A_s' f_y'$ $M_u \le \varnothing M_n = \varnothing\left[0.85 f_c' ab\left(d - \frac{a}{2}\right) + A_s' f_y'(d - d')\right]$
EC 2 （欧洲规范）	$\eta f_{cd}(\lambda x) b = A_s f_{yd} - A_s' \sigma_s'$ $M_{Ed} \le M_{Rd} = \eta f_{cd}(\lambda x) b\left(d - \frac{\lambda x}{2}\right) + A_s' \sigma_s'(d - d')$

LC3 concrete: GB, EC 2 and ACI 318

Specimens	M_u（kN·m）	M_{GB}（kN·m）	M_u/M_{GB}	M_{ACI}（kN·m）	M_u/M_{ACI}	M_{EN}（kN·m）	M_u/M_{EN}
LCC-45-L	143.2	113.8	1.26	101.1	1.42	113.8	1.26
LCC-45-M	209.5	170.8	1.23	150.5	1.39	170.8	1.23
LCC-45-H	232.2	200.0	1.16	174.8	1.33	200.0	1.16
LCC-50-M	211.0	172.0	1.23	151.8	1.39	172.0	1.23
LCC-60-M	223.3	177.1	1.26	157.3	1.42	177.2	1.26
Mean. Std.	—	—	1.23 0.04	—	1.39 0.03	—	1.23 0.04

Normal concrete: GB, EC 2 and ACI 318

Specimens	M_u（kN·m）	M_{GB}（kN·m）	M_u/M_{GB}	M_{ACI}（kN·m）	M_u/M_{ACI}	M_{EN}（kN·m）	M_u/M_{EN}
PCC-45-L	148.9	112.4	1.32	99.7	1.49	112.4	1.32
PCC-45-M	213.0	167.4	1.27	146.9	1.45	167.4	1.27
PCC-45-H	238.9	194.5	1.23	168.9	1.41	194.5	1.23
PCC-50-M	210.1	168.5	1.25	148.1	1.42	168.5	1.25
PCC-60-M	217.4	174.9	1.24	155.1	1.40	175.1	1.24
Mean. Std.	—	—	1.26 0.03	—	1.44 0.03	—	1.26 0.03

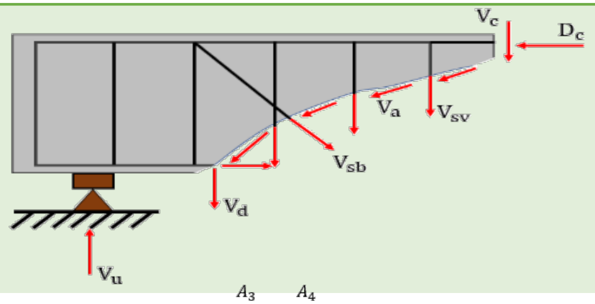
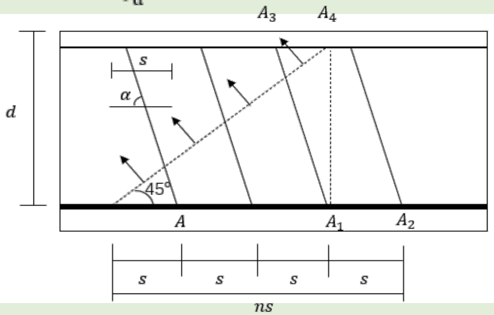
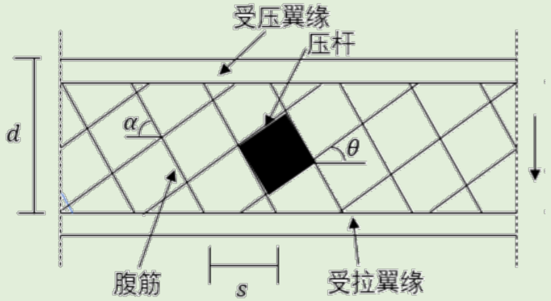
Note：M_u=test results；M_{GB}=GB results；M_{ACI}=ACI results；M_{EN}=EC 2 results .

GB 50010, EC 2 predictions are closer to the flexural resistance of reinforced-LC³concrete members.

3.3 Code predictions and assessments of flexural and shear resistance

(2) Prediction and assessment of shear resistance

Shear resistance models in different design codes

Codes	Calculation model and formulae
GB50010 (中国规范)	 $V_u = V_c + V_{sv} + V_{sb} + V_d + V_a$ $V_u = V_{cs} + 0.8 f_y A_{sb} \sin\alpha_s$ $V_{cs} = \frac{1.75}{\lambda+1} f_t b h_0 + f_{yv}\frac{A_{sv}}{s} h_0$
ACI 318 (美国规范)	 $V_u \le \varnothing V_n = \varnothing (V_c + V_s)$ $V_c = 0.166\sqrt{f_c'} b_w d$ $V_s = \frac{A_v f_y d}{s} \le 0.665\sqrt{f_c'} b_w d$
EC 2 (欧洲规范)	 $V_{Rd,s} = \frac{A_{sw} f_{ywd} z}{s}(\cot\theta + \cot\alpha)\sin\alpha$ $V_{Rd,max} = \alpha_{cw} v_1 f_{cd} b_w z \frac{\cot\theta + \cot\alpha}{1+\cot^2\theta}$

3.3 Code predictions and assessments of flexural and shear resistance

(2) Prediction and assessment of shear resistance

LC3: GB, EC 2 and ACI 318

Specimens	V_u (kN)	V_{GB} (kN)	V_u / V_{GB}	V_{ACI} (kN)	V_u / V_{ACI}	V_{EU} (kN)	V_u / V_{EU}
LCC-45-M-1.5	389.4	271.5	1.43	139.4	2.79	128.3	3.03
LCC-45-M-2	304.3	238.1	1.28	139.4	2.18	128.3	2.37
LCC-45-M-2.5	223.6	214.3	1.04	139.4	1.60	128.3	1.74
LCC-45-L-2	251.9	220.3	1.14	121.6	2.07	96.2	2.62
LCC-45-H-2	361.5	273.8	1.32	175.1	2.06	192.5	1.88
LCC-50-M-2	280.5	256.7	1.09	141.6	1.98	128.3	2.19
LCC-60-M-2	359.3	291.4	1.23	154.0	2.33	128.3	2.80
Mean.			1.22		2.15		2.38
Std.			0.14		0.36		0.48

Normal concrete: GB, EC 2 and ACI 318

PCC-45-M-1.5	389.9	254.6	1.53	134.3	2.90	128.3	3.04
PCC-45-M-2	283.1	224.1	1.26	134.3	2.11	128.3	2.21
PCC-45-M-2.5	252.6	202.2	1.25	134.3	1.88	128.3	1.97
PCC-45-L-2	236.6	206.3	1.15	116.5	2.03	96.2	2.46
PCC-45-H-2	291.4	259.7	1.12	170.0	1.71	192.5	1.51
PCC-50-M-2	315.0	241.0	1.31	135.8	2.32	128.3	2.45
PCC-60-M-2	292.9	275.0	1.07	148.3	1.98	128.3	2.28
Mean.			1.24		2.13		2.27
Std.			0.15		0.39		0.47

$$V_{cs} = \frac{1.75}{\lambda+1} f_t b h_0 + f_{yv} \frac{A_{sv}}{s} h_0 \qquad V_c = 0.166\sqrt{f_c'} b_w d \qquad V_{Rd,max} = \alpha_{cw} v_1 f_{cd} b_w z \frac{\cot\theta + \cot\alpha}{1+\cot^2\theta}$$

Huang et al. Structural Concrete. 2023;1–23.

GB 50010 predictions are more precise than other codes.

ACI and EC 2 provide more conservative perditions.

Highlights:

1.GB 50010 uses f_t to represent the concrete contribution while EC 2 and ACI both use f_c.

2. Shear-span effect is ignored in EC 2

3.Most codes/research use f_c rather than f_v, f_t to represent shear/tensile resistance (indirect way), which may cause prediction errors.

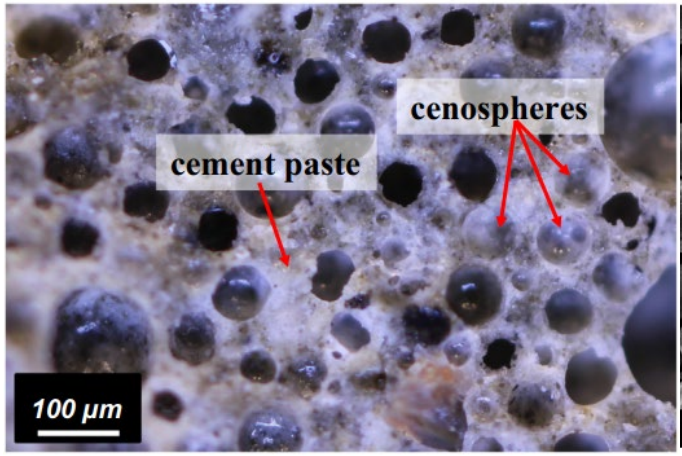
Outline

1. Introduction
2. Development of LC^3 concrete based on local resources
3. Structural behavior of reinforced LC^3 concrete members
4. **Durability performance of LC^3-based ULCC against chloride ingression and carbonation**
5. Development and application of LC^3 based lightweight core-shell aggregate concrete
6. Conclusions

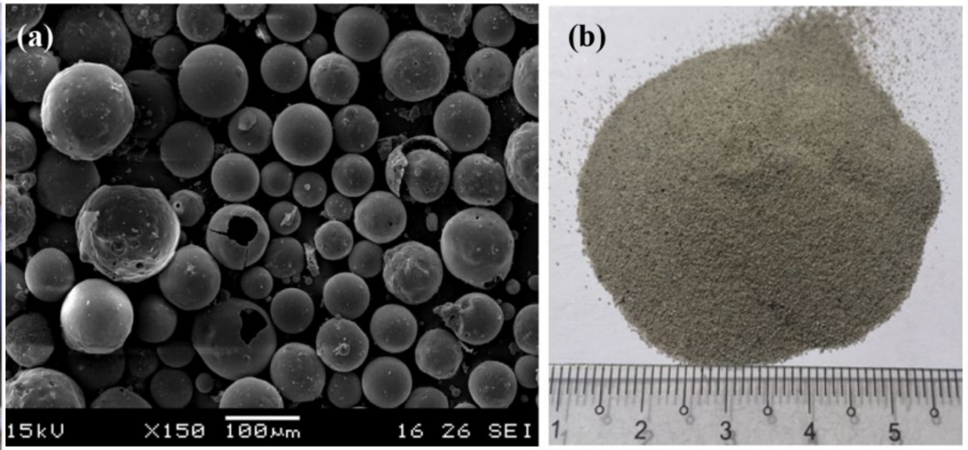
04 Durability performance of LC^3-based ULCC against chloride ingression and carbonation

Ultra-lightweight cement composite (ULCC) 超轻质水泥基复合材料

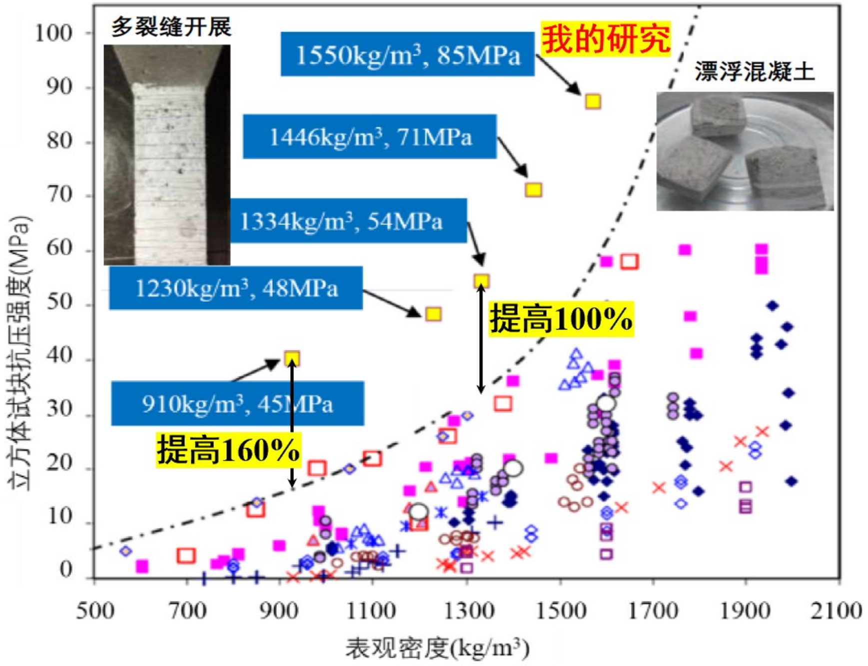
density less than 1550kg/m³ with structural strength(40-85MPa)



Microstructure of ULCC



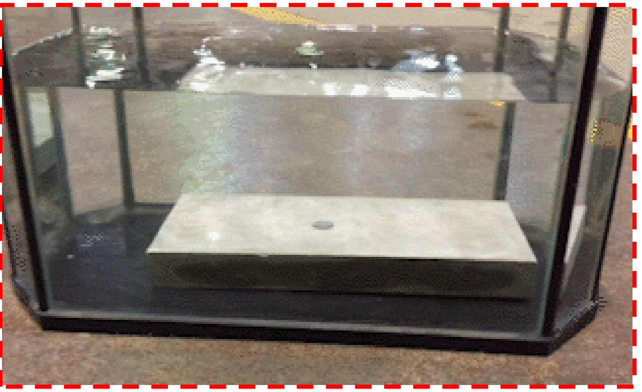
Fly ash cenospheres



Mixture proportions of ULCC with water/binder ratio of 0.33.

Mix ID	Fibre type	Fibre content (vol%)	Mixture proportion of matrix by mass of total binder			
			Binder			Cenosphere/b % by volume
			Cement	Silica fume	Fly Ash	
ULCC-N	–	0	0.92	0.08	0	0.42
ULCC-02PP	PP	0.2				
ULCC-05PP	PP	0.5				
ULCC-1PP	PP	1.0				
ULCC-02PP08S	PP + Steel	0.2 + 0.8				
ULCC-1S	Steel	1.0				
ULCC-02PP15FA	PP	0.2	0.78		0.14	
ULCC-02PP30FA	PP	0.2	0.64		0.28	

PP = polypropylene fibre, SRA = Shrinkage reduced admixture; S = Steel fibre, FA = fly ash, SP = superplasticizer.



Limitations:

1.High cement content：high carbon footprint

2.High porosity：lower elastic modulus, easy to crack

Low carbon LC^3-based ULCC

Zhenyu Huang, J.Y.Richard Liew, Wei Li. Evaluation of compressive behavior of ultra-lightweight cement composite after elevated temperature exposure. Construction and Building Materials, 2017, 148: 579-589.

04 Durability performance of LC³-based ULCC against chloride ingression and carbonation

50-2:1=50%cement, calcined clay/limestone=2:1

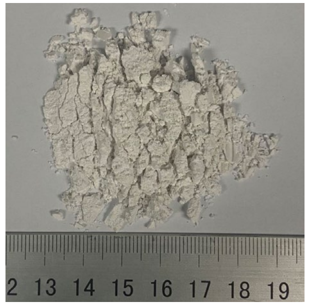
Mix design of ULCC-LC³

Group	OPC (kg/m³)	Calcined clay (kg/m³)	Limestone (kg/m³)	Gypsum (kg/m³)	Cenosphere (kg/m³)	Silica fume (kg/m³)	Water (kg/m³)	Superplasticizer (kg/m³)	SRA (kg/m³)	PE fiber (%)
ULCC	873.9	0	0	0	287.6	97.1	264.9	4.3	9.3	0
50-1:1	464.0	196.6	196.6	16.6	287.6	97.1	264.9	6.5	9.3	0
50-2:1	464.0	262.2	131.1	16.6	287.6	97.1	264.9	8.3	9.3	0
50-3:1	464.0	294.9	98.3	16.6	287.6	97.1	264.9	8.5	9.3	0
45-2:1	418.6	291.3	145.7	18.4	287.6	97.1	264.9	9.0	9.3	0
65-2:1	600.4	174.8	87.4	11.4	287.6	97.1	264.9	6.7	9.3	0
ULCC-1	873.9	0	0	0	287.6	97.1	264.9	4.6	9.3	1
50-1:1-1	464.0	196.6	196.6	16.6	287.6	97.1	264.9	6.9	9.3	1
50-2:1-1	464.0	262.2	131.1	16.6	287.6	97.1	264.9	8.7	9.3	1
50-3:1-1	464.0	294.9	98.3	16.6	287.6	97.1	264.9	9.1	9.3	1
45-2:1-1	418.6	291.3	145.7	18.4	287.6	97.1	264.9	9.6	9.3	1
65-2:1-1	600.4	174.8	87.4	11.4	287.6	97.1	264.9	7.0	9.3	1

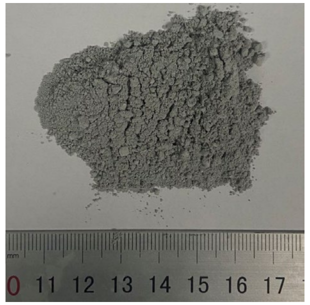

Cement

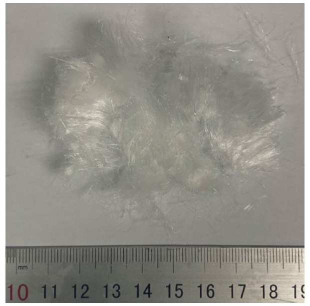

Cenosphere

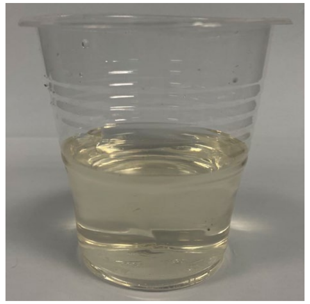

Calcined clay


Limestone


Gypsum

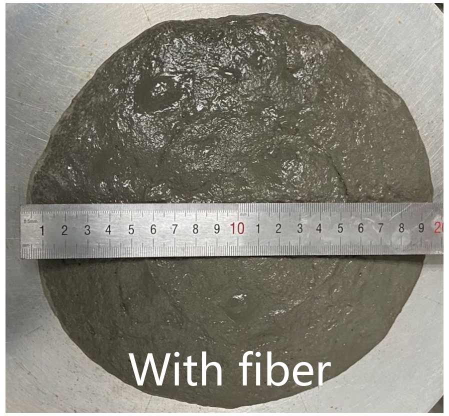

Silica fume


PE fiber

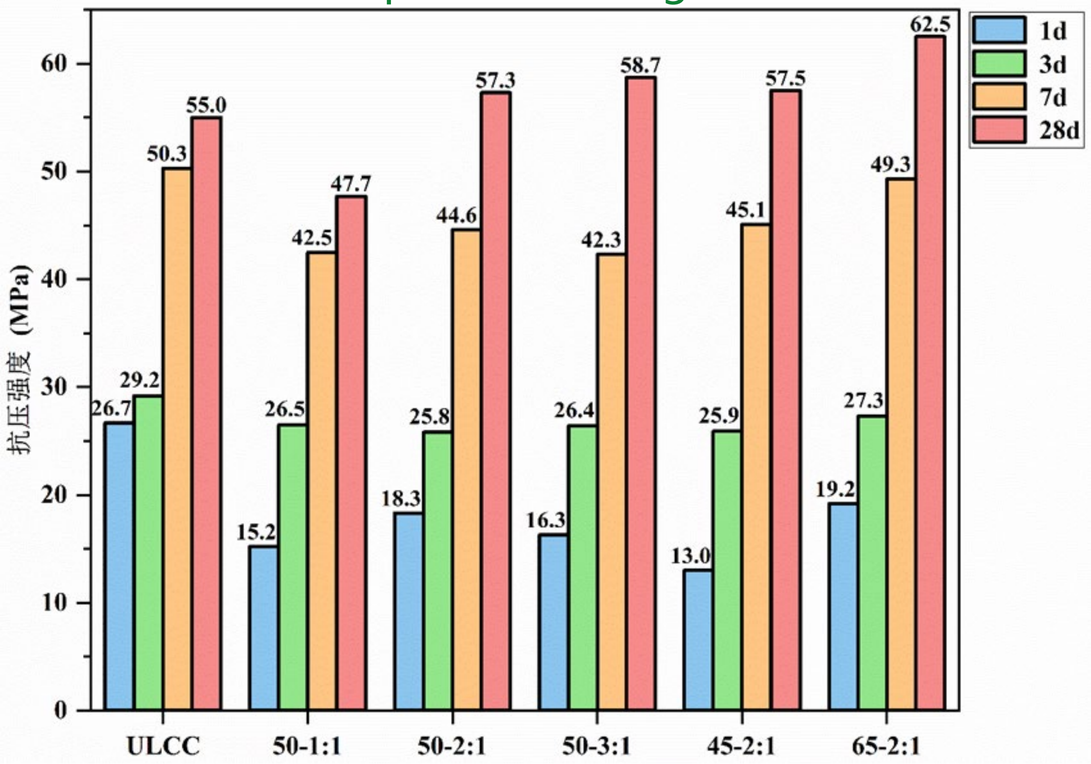

Superplasticizer

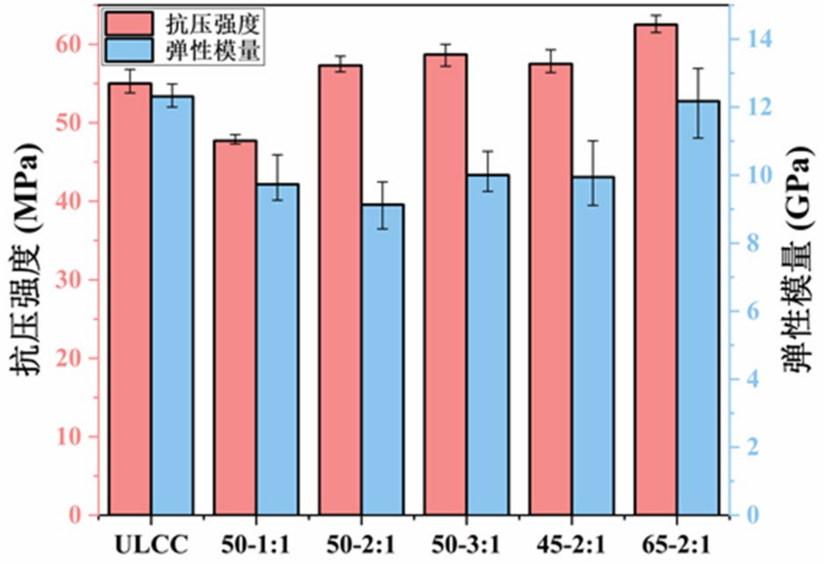
Zhenyu HUANG, Tingting LIANG, Lijie CHEN.Experimental studies on durability performances of ultra-lightweight low-carbon LC3 cement composites against chloride ingression and carbonation. Construction and Building Materials. 2023,395,132340.

04 Durability performance of LC^3-based ULCC against chloride ingression and carbonation

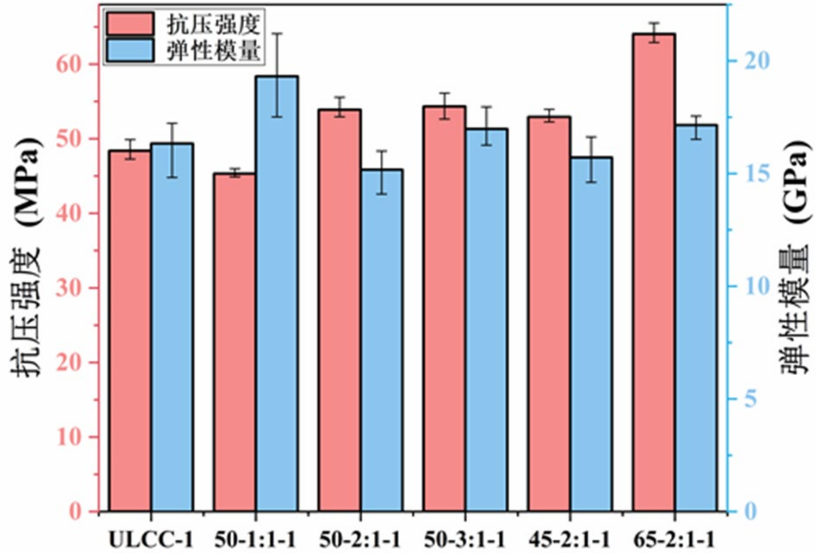


Compressive strength





Without fiber

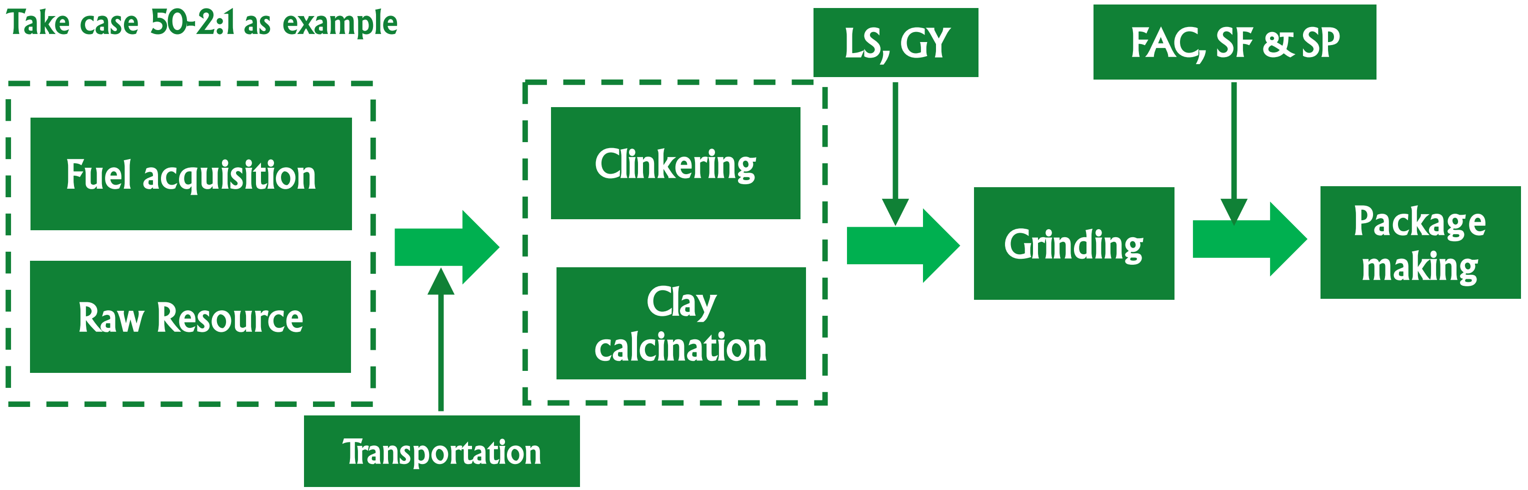


With fiber

- **Good workability:**181-205mm
- **Density range:**1510.6-1567.0kg/m³，much lower than《轻骨料混凝土应用技术标准 JGJ/T 122019》-1950 kg/m³
- **Strength:** Comparable compressive strength, but lower elastic modulus

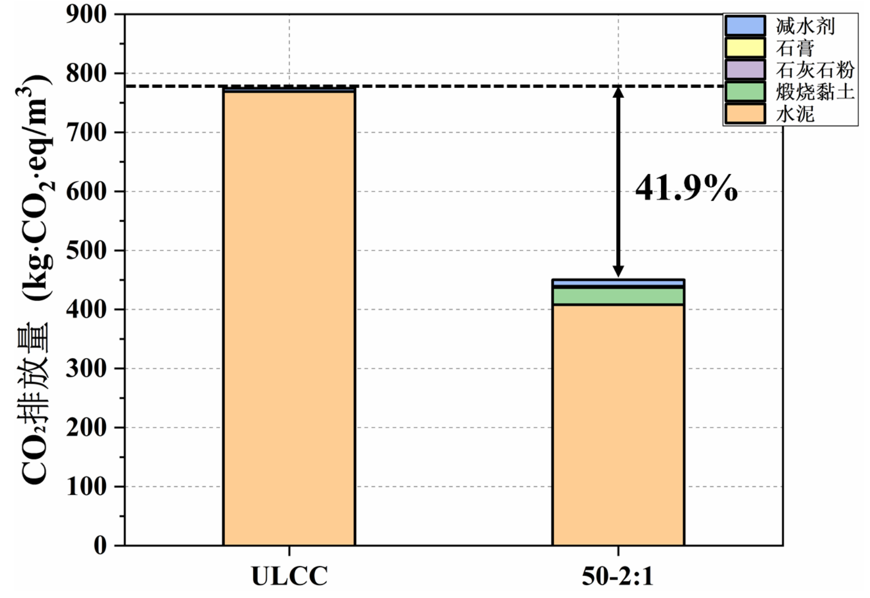
04 Durability performance of LC³-based ULCC against chloride ingression and carbonation

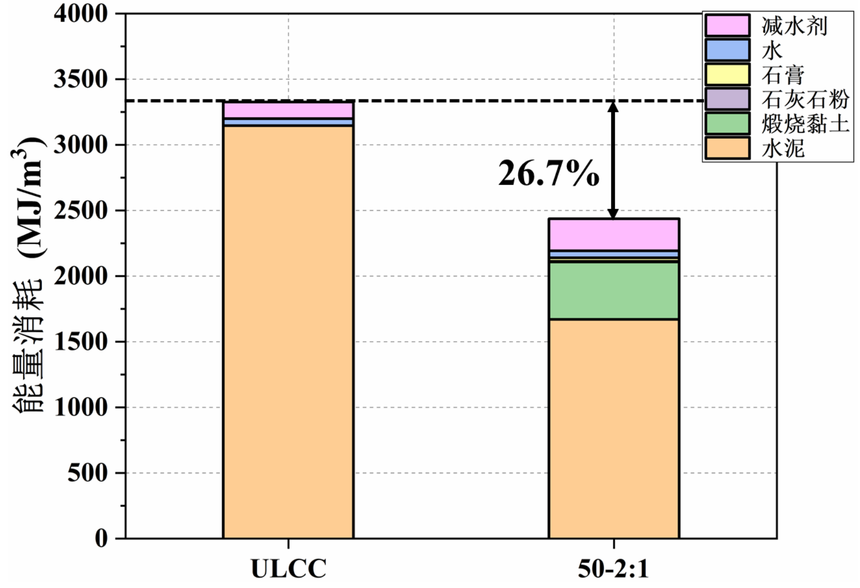
Life Cycle Assessment（LCA）生命周期评估



系统边界：从“开采”到“大门”—— “from cradle to gate”

- CO2 emission and energy consumption is largely from cement;
- Compared to ULCC, the use of LC^3 effectively reduce CO2 (41.9%) and energy consumption (26.7%)





LCA was performed using the GaBi software, in accordance with the ISO 14040 and ISO 14044.

04 Durability performance of LC^3-based ULCC against chloride ingression and carbonation

快速氯离子迁移系数法(GB/T 50082)

Rapid Chloride Migration Method (RCM)

Test setup

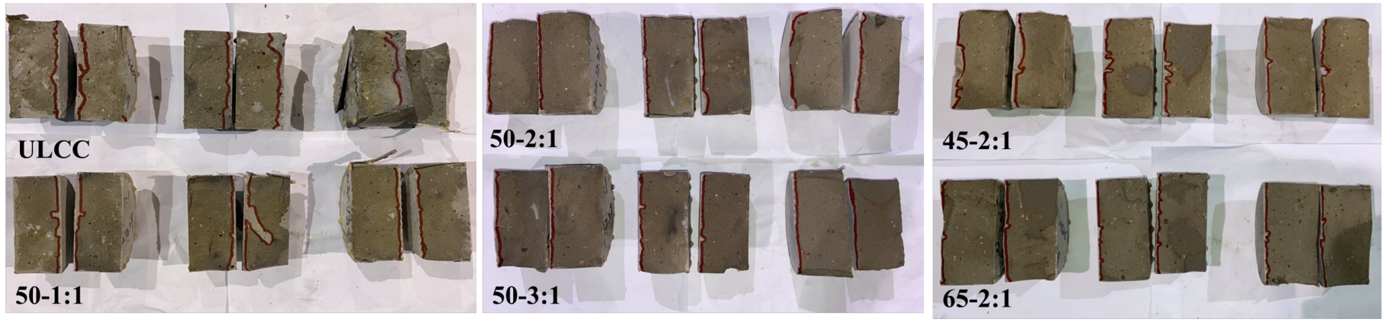
ϕ50mm×ϕ100mm samples

Chloride ion migration coefficient：

$$D_{RCM}=\frac{0.0239\times(273+T)L}{(U-2)t}\left(X_d-0.0238\sqrt{\frac{(273+T)LX_d}{U-2}}\right)$$

RCM test results

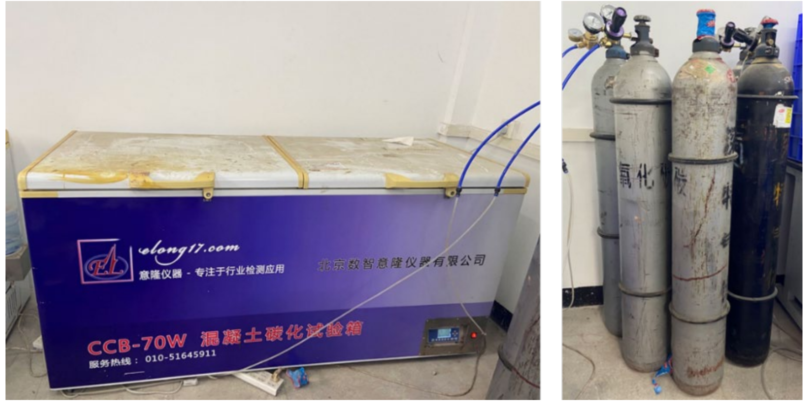
ID		Tem (℃)	Thickness（mm）	渗透深度（mm）	Time（h）	电压（V）	氯离子迁移系数 ($10^{-12}m^2/s$)	迁移系数平均值($10^{-12}m^2/s$)
ULCC	1	24.40	51.3	9.6	24	60	2.2(剔除)	1.2
	2	24.35	51.3	5.3	24	60	1.2	
	3	24.40	51.5	5.2	24	60	1.1	
50-1:1	1	25.35	50.0	4.4	24	60	0.9	0.8
	2	25.40	50.3	4.0	24	60	0.8	
	3	25.35	50.7	2.9	24	60	0.6	
50-2:1	1	24.60	51.8	2.6	24	60	0.5	0.6
	2	24.40	51.9	3.3	24	60	0.7	
	3	24.15	50.1	3.5	24	60	0.7	
50-3:1	1	24.50	51.7	2.1	24	60	0.4	0.5
	2	24.45	51.5	2.9	24	60	0.6	
	3	24.50	51.2	2.2	24	60	0.4	
45-2:1	1	25.05	50.1	6.1	24	60	1.3	1.0
	2	25.00	50.3	4.5	24	60	1.0	
	3	24.75	50.7	3.7	24	60	0.8	
65-2:1	1	25.10	51.8	2.6	24	60	0.5	0.6
	2	24.90	51.6	2.9	24	60	0.6	
	3	24.90	51.7	2.9	24	60	0.6	



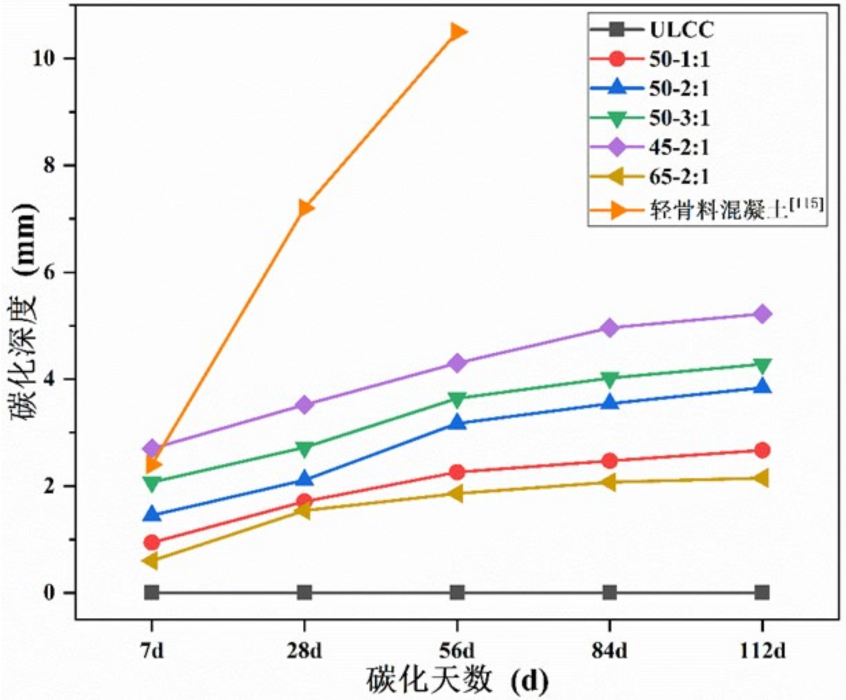
Comparison of chloride penetration depth for test samples

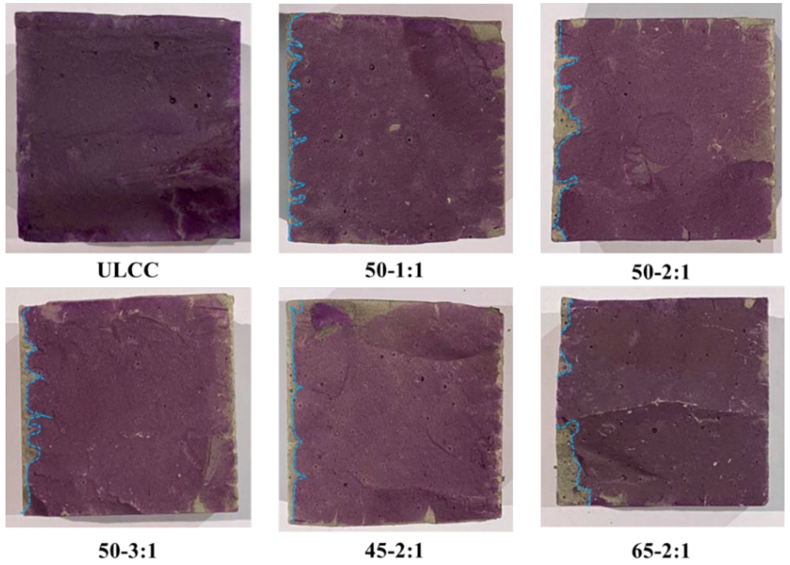
04 Durability performance of LC^3-based ULCC against chloride ingression and carbonation

加速碳化试验Accelerated carbonation tests (GB/T 50082)

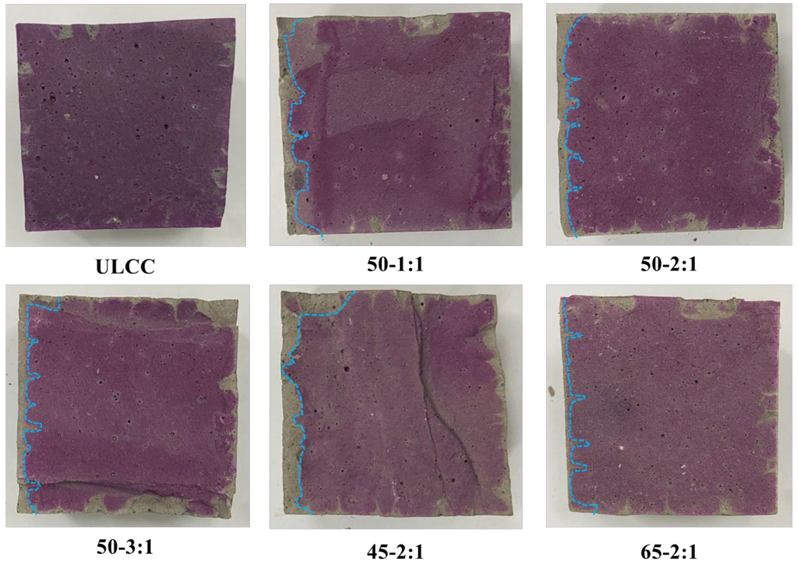


Test setup





Carbonation depth at 7 day



Carbonation depth at 28 day

- Use of LC^3 reduces the carbonation resistance, resulting in an increased carbonation depth.
- Still better than normal lightweight aggregate concrete.

Outline

05 Development and application of LC^3 based lightweight core-shell aggregate concrete

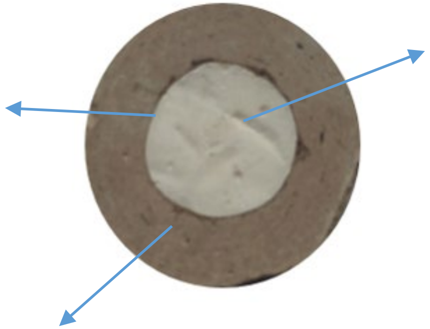
CBM,2018,170:757-775

Sintering method 烧结法

Expanded clay/shale aggregate

High carbon emission & energy demand (Rotary kiln temperature up to1200°C)

Core-shell aggregate



EPS

Bond

Cementitious material

Cold-bond method 冷粘法

Low carbon emission & energy demand (Room temperature production)


证书号第 5072025 号

发明专利证书

发 明 名 称：冷粘法制备核壳结构轻骨料及其制备方法

发 明 人：黄振宇；邓伟雄；李康宇；马红岩；崔宏志；周英武；陈莉莉 余鑫

专 利 号：ZL 2020 1 1299624. X

专利申请日：2020 年 11 月 19 日

专 利 权 人：深圳大学

地 址：518060 广东省深圳市南山区南海大道 3688 号

授权公告日：2022 年 04 月 12 日 授权公告号：CN 112194400 B

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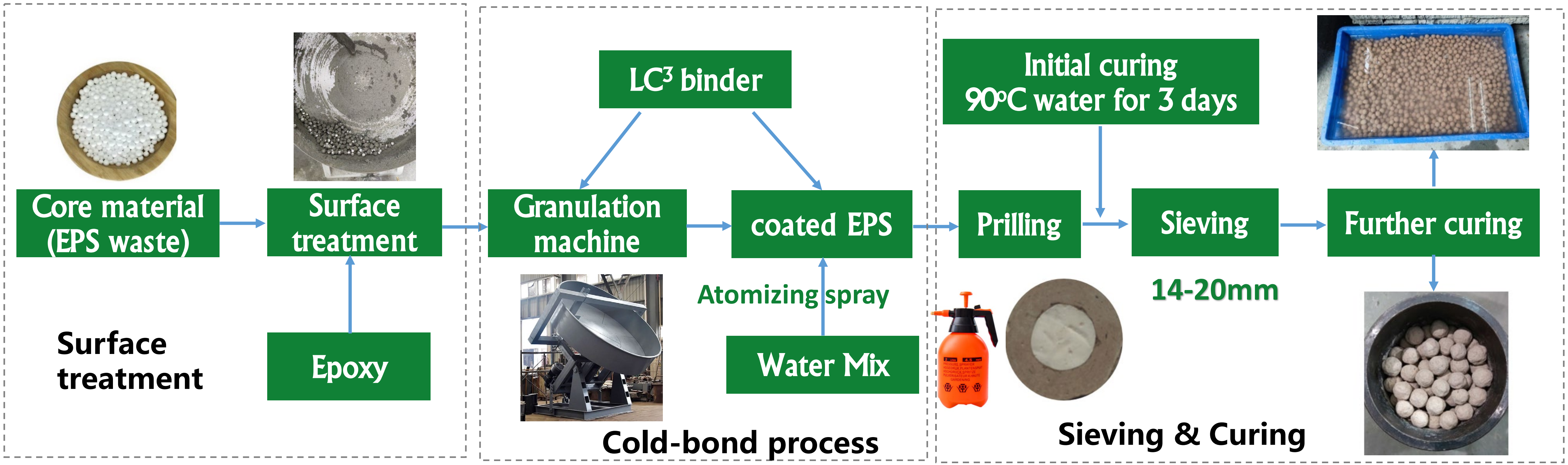
局长 申长雨

第 1 页 (共 2 页)

黄振宇等，冷粘法制备核壳结构轻骨料及其制备方法.中国发明专利: ZL 202011299624.X

05 Development and application of LC^3 based lightweight core-shell aggregate concrete

Core-shell lightweight aggregates production → **Non-structural partition wall**



05 Development and application of LC^3 based lightweight core-shell aggregate concrete

LC^3 binder proportion

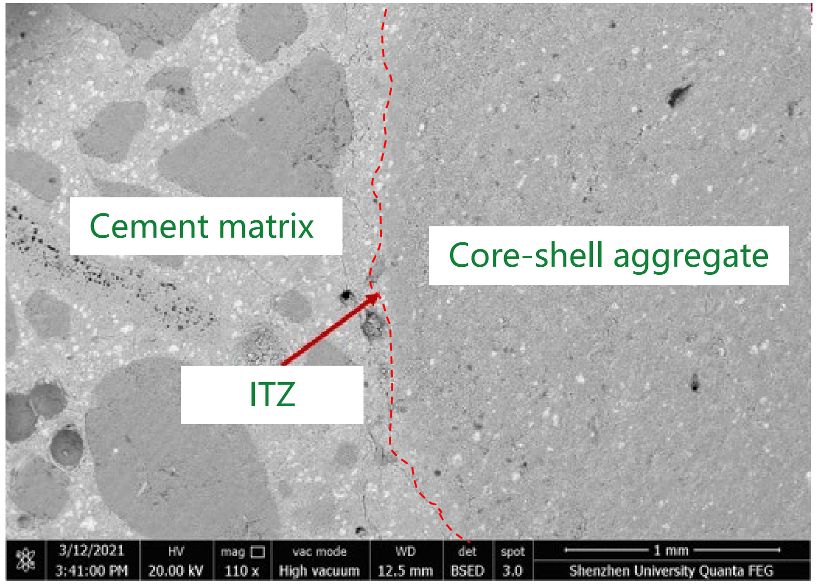
ID	Core material	Shell material			
		OPC（%）	CC（%）	LS（%）	GY（%）
LC^3-50-2:1	8-10mm EPS	50	30	15	5

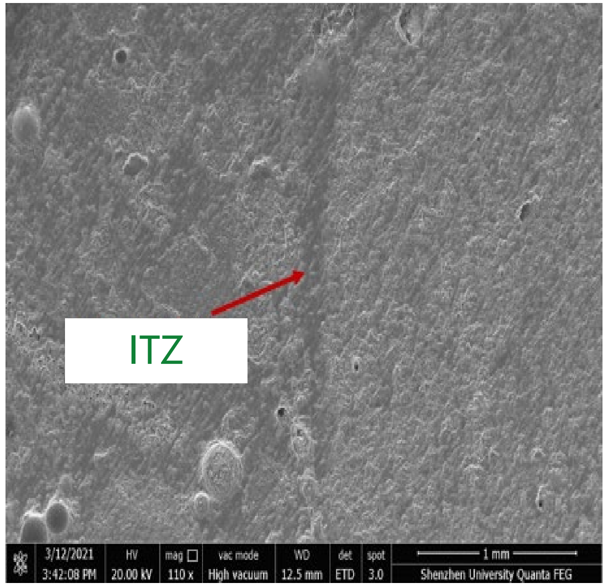
Physical properties of core-shell lightweight aggregate

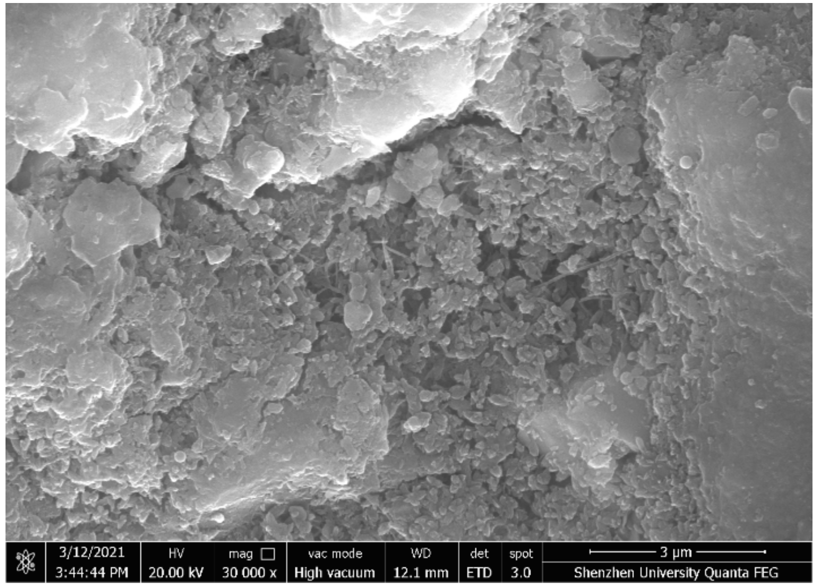
ID	Size (mm)	Apparent density（kg/m^3）	Bulk density（kg/m^3）	筒压强度（MPa）	1h吸水率（%）	24h吸水率（%）
LC3-50-2:1	14-20	1546	843	8.7	4.85	5.68

Calcined clay: limestone=2:1，speed/angle/water..., to achieve the highest compressive strength

05 Development and application of LC^3 based lightweight core-shell aggregate concrete



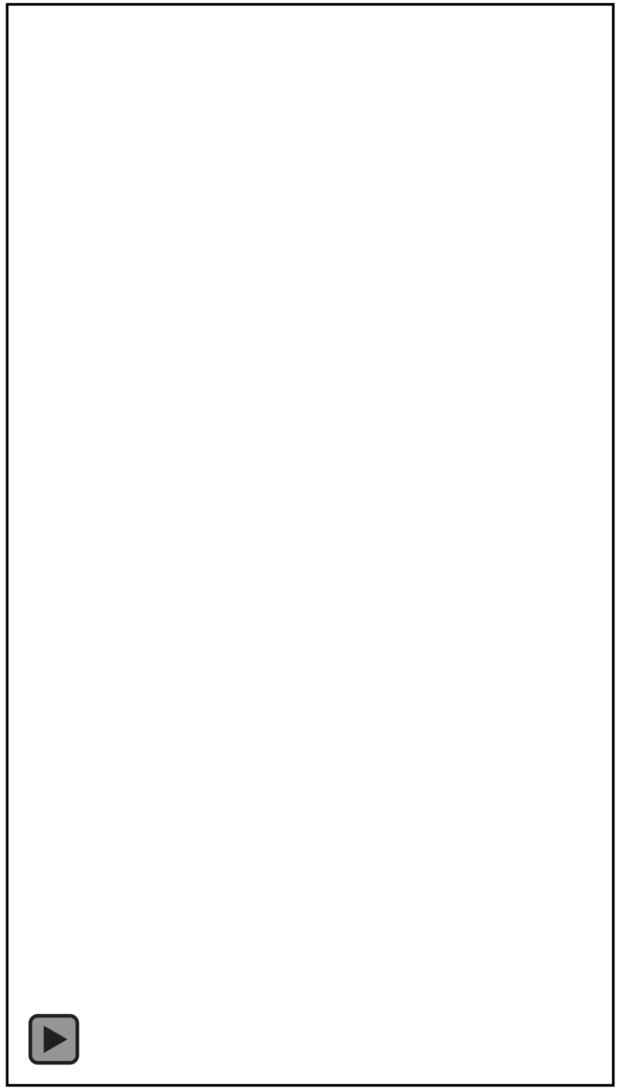




- ITZ is difficult to discern.
- Core-shell material closely resembles the cement matrix, resulting in good contact between aggregate and paste.
- Aggregate surface undergoes secondary hydration to produce hydration products to form a denser ITZ.

05 Development and application of LC^3 based lightweight core-shell aggregate concrete

Granulation machine



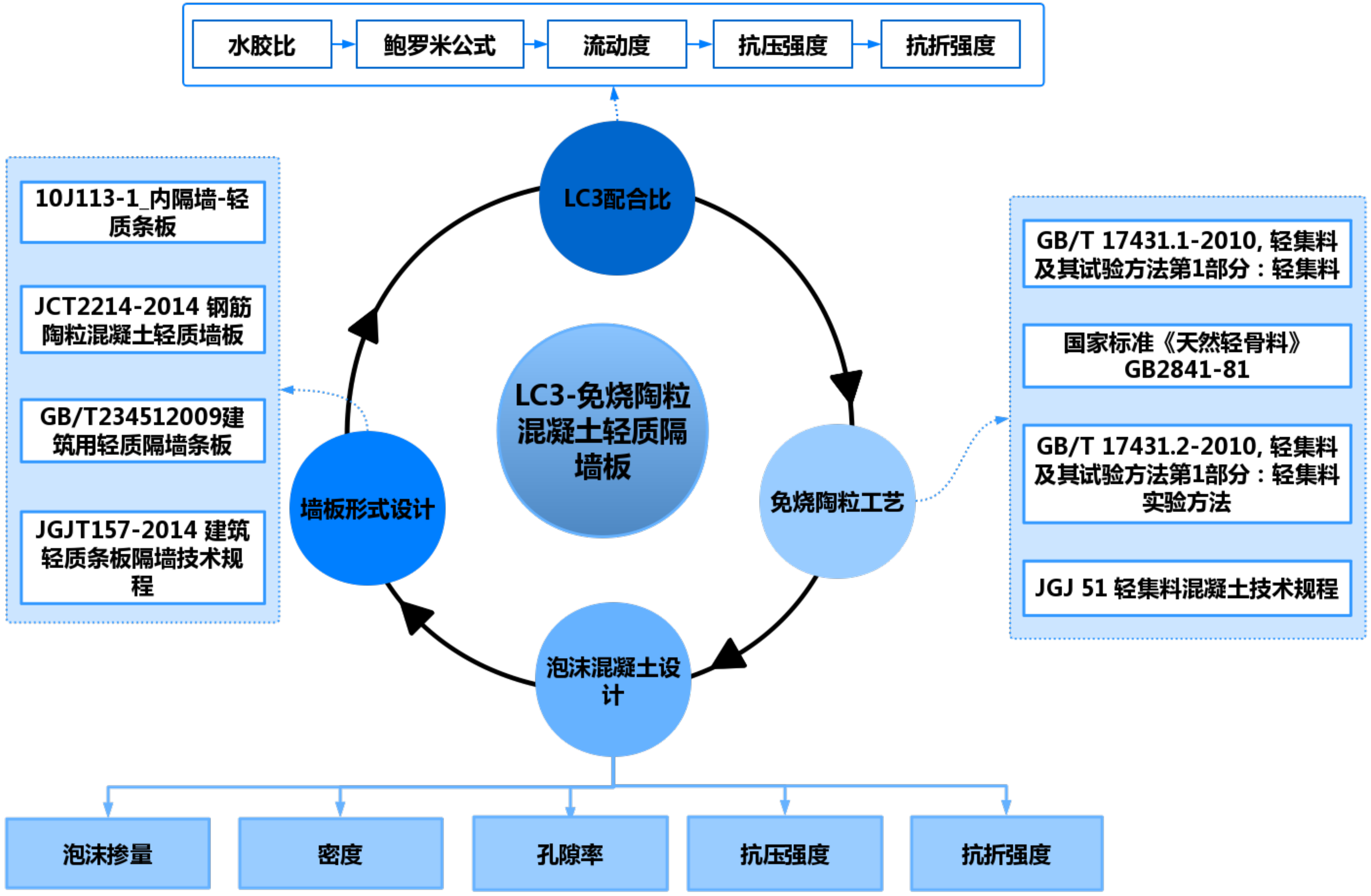
Granulation process

Sealed for 1d

water curing

Core-shell lightweight aggregate

05 Development and application of LC³ based lightweight core-shell aggregate concrete



Production of Core-shell lightweight panel

Curing and production

05 Development and application of LC^3 based lightweight core-shell aggregate concrete

深圳市光明区“2022金地管理•峰境瑞府”主体工程示范应用

Core-shell lightweight panel

深圳大学 SHENZHEN UNIVERSITY

中建四局第五建筑工程有限公司 CCFED THE FIFTH CONSTRUCTION & ENGINEERING CO.

06 Conclusions

For normal concrete:

(1) Develop a new type of green cement concrete using LC^3

(2) Conduct tests of compression, splitting, bond behavior, flexural and shear behavior as compared to convectional RC beams.

(3) Assessment of current flexural and shear design formulae.

(4) LC3 concrete has higher splitting-compression ratio （折压比）: fc or ft?

For lightweight ULCC:

(1) Develop low-carbon LC^3-based ULCC with low density (1500 kg/m^3) and high strength.

(2) The use of LC^3 significantly decreases the carbon emission and energy consumption.

(3) The chloride resistance of ULCC-LC^3 is significantly improved as compared with ULCC and normal concrete which is due to the refined pore structure and increased chloride binding capacity.

(4) LC^3 can effectively densify the porosity, reduce the chloride migration coefficient. In accelerated carbonation tests, LC^3 lowers the carbonation resistance.

06

Conclusions

Further research:

(1) Improve early strength of LC^3 concrete;

(2) Evaluate long term (durability) structural behavior for marine civil engineering;

(3) LC^3 standards;

(4) Resources, Superplasticizers...

References & Acknowledgement

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Thank you!

谢谢！敬请批评指正！

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