Advances in Civil Engineering Materials
土木工程材料进展

SHI, Caijun (史才军) Ph.D., P. Eng. FACI

Professor
Civil Engineering College, Hunan Univ.
（湖南大学土木学院 教授）

caijunshi@yahoo.com

个人简介 - 学术任职

- 美国土木工程学会期刊《土木工程材料》副主编
- Elsevier著名学术期刊《水泥和混凝土研究》和《水泥和混凝土复合材料》编委
- 中国硅酸盐学会《硅酸盐学报》编委
- 美国混凝土学会(ACI)中的8个专业委员会的会员
- 美国材料与测试学会(ASTM) 中的4个专业委员会的会员
- 加拿大标准协会(CSA)中的2个专业委员会的会员
- 国际材料与结构研究实验联合会(RILEM)的高级会员及2个专业委员会的会员
- 中国硅酸盐学会水泥专业委员会、化学激发胶凝材料分会副主任委员
- 担任国际上30多个土木工程材料与环境领域的著名学术期刊的审稿人。
- 中南大学讲座教授、博士生导师
- 纽约州立大学水牛城分校、南京工业大学、武汉理工大学兼职教授
- 重庆大学、华南理工大学客座教授

Main Achievements/主要学术成果

- 发表论文140余篇，论文他引1400多次；
- 出版英文著作5本，合编国际会议论文集3本；
- 组织和主持国际学术会议3次和专题研讨会3次；
- 20余次应邀担任专家委员会委员或分会主席；
- 多次应邀做大会主题报告和大会报告；
- 应邀在国际上近40所大学和大公司做学术报告和专题讲座；
- 应邀当过国际上近30多个著名学术期刊的审稿人；

Books/著作

Contents

- Construction in China
- Cement Industry in China
- Concrete Industry in China
- High Performance Concrete
- Self-consolidating Concrete
- Lightweight Concrete
- Durability of Concrete Materials and Structure
- Thermal Insulation System
- Smart Self-repairing Barrier

China – A Large Construction Site

Urbanization

- 30% of the population live in cities now, but will increase to 70% in the future;
- Huge amount of Infrastructure and residential buildings will be built to meet the demand of rapid urbanization in China.

Production of cement and steel in China

	Cement Production (MMT)	% of global Production	Steel Production (MMT)	% of global Production
2008	**1,380**	**About 50%**	**500 Mil.**	**About 38%**
2009	**1,630**	**About 53%**	**678 Mil**	**About 50%**
Increased %	**17.9%**		**13.5%**	

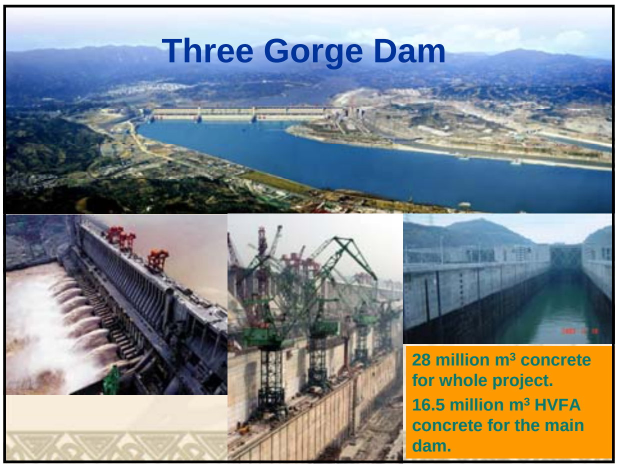
Based on the production of cement and steel, the construction in China is more than 50% of the total global construction

Planned big projects

- There are lots of infrastructure projects such as high speed railways, highways, bridges, tunnels, subways, power stations, *et al*.

Huge amount of cement and concrete are needed!


Concrete in our lives
Hunan University


Three Gorge Dam
28 million m³ concrete for whole project.
16.5 million m³ HVFA concrete for the main dam.

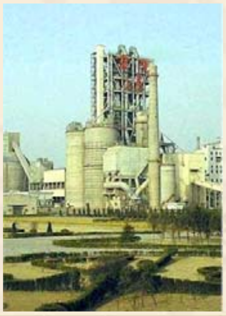

New CCTV Center
Two towers which are 234m high, and incline 6 degree.
There is a 14 floor cantilever that stretches out 75m long.
The building area is 495,000 m², largest single building

Hangzhou Bay Bridge

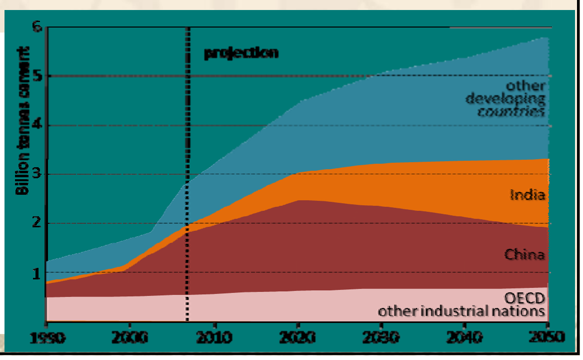
- 36 km long, 100 km/h
- 100 years service life
- 769,000 t steel
- 129,100 t cement
- 240,000 m^3 concrete
- 11 Billion RMB

Hunan University

Cement industry in China



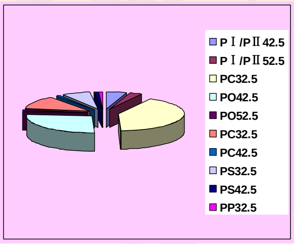
Prediction of World Cement Production



Chinese Standard for Cement

Name	Symbol	Clinker+ gypsum[1]	SCM			
			Slag[2]	Pozzolan[2]	Fly Ash[2]	Other Material[4]
PC	P. I、 P. II	100% 100~95%	/ /	/ /	/ /	/ 0~5%
OPC	P. O	94~80%	6~20%			0~5%
Portland Slag Cement	P. S（A） P. S（B） P. S（C）	79~65% 64~50% 49~30%	21~35% 36~50% 51~70%	/	/	0~5%
Portland Pozzolan Cement	P. P	79~60%	/	21~40%	/	0~5%
Portland Fly Ash Cement	P. F	79~60%	/	/	21~40%	0~5%
Portland Composite Cement	P. C	79~50%	21~50%[3]			0~5%

Different Types of Cements in China in 2005



- PC I & II 8%
- PO 28%
- PC 55%
- Portland Slag Cement 8%
- Portland Pozzolan Cement 1%

Distribution of strength class of cement

Year	Country	strength class			
		32.5	42.5	52.5	62.5
2007	China	55.3%	40.6%	3.9%	0.2%
1997	Germany	61.6%	32.4%	5.7%	--
1997	France	48.2%	11.3%	32.6%	--

SCMs in Cements

Max 26%	Max 48%
P.O 42.5	P.O 32.5
Average 20%	Average 28% (40%?)

In 2010, the clinker content in cement is 61.67%, about 3% less than in 2009!

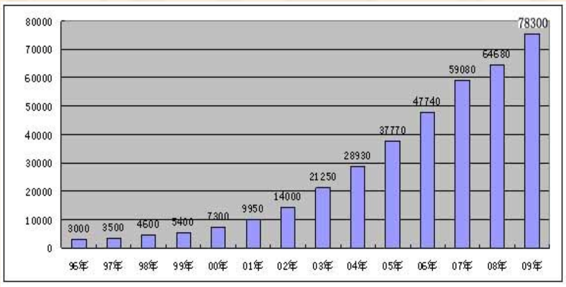
2001年的150kgce/t下降到2007年的126 kgce/

Change in Cement Production Process

Year	Total Cement Production (MT)	Rotary Kiln Production (%)
2001	664,000,000	14
2008	1,388,000,000	62
2010	1,868,000,000	80

Concrete Production in China

Ready Mixed Concrete Production in China



Production of ready-mixed concrete（*10 thousand m^3）

General

- Most concrete is cast on site, About 790 million m^3 concrete is ready-mixed in stations, the rest is mixed on site.
- 10% is used for prefabricated concrete elements.
- About 40% concrete uses chemical admixture.

Production of ready-mixed concrete in several large cities in 2009

City	Output (million m^3)	Increase rate (%)
Beijing	39.6	8.0
Shanghai	60.5	9.4
Chongqinag	22.0	4.3
TianJin	26.7	33.5

Chemical admixture

- Extensive use of chemical admixture in concrete began in 80s, last century.
- The main ones include water reducer, then retarder, accelerator, air-entrainer, pumping aid, anti-freezing agent, *et al*.

Water reducer

- The Production of superplasticizer is 4.85 million ton in 2009, 55% Naphthaline-type superplasticizer, 26% polycarboxyate.
- 我国聚羧酸减水剂生产企业已有百余家。2000年，我国聚羧酸减水剂产量仅2000吨，2006年为15万吨，2007年已发展到41.43万吨，2009年产量达到了126.83万吨。

Mineral admixture

- More than 100 million ton of mineral admixture is used in concrete industry.
- Main ones are **fly ash** and **ground granulated blast furnace slag (GGBS)**.

The technical specifications for fly ash used in concrete

Index	Grade		
	I	II	III
The residue of sieve(0.045mm) , % ≤	12	20	45
Water demand ratio, % ≤	95	105	115
Loss on ignition， % ≤	5	8	15
Water content, % ≤	1	1	No requirement
SO_3, % ≤	3	3	3

Usage of fly ash in concrete industry

- Fly ash becomes an indispensable composite in ready-mixed concrete.
- Fly ash is normally 10-30% of binder.
- As high as 50% fly ash is used to produce massive concrete.

Usage of GGBS in concrete

- The used amount of GGBS increases gradually. Several GGBS millworks with million ton capability were built by steel enterprises.
- Ground steel slag went to market recently.
- A little of silica fume is used only for high strength concrete.

Aggregate Supply

- There is not enough supply of aggregate in large cities.
- Aggregate should be transported 100 km long from neighbor area.
- Sand is seriously absent. Manufactured sand is more and more used together with natural river sand.
- Utilization of recycled concrete as aggregate is being developed.

Largest challenges

- How to make industry

use of high performance concrete

The country needs:

Less resource and energy consumption;

more durable structure;

utilization of more industrial waste

Major technical progress in concrete materials in China

- A variety of high performance concrete developed and used
- Durability design Code for concrete materials and structures

High Performance Concrete

HIGH PERFORMANE CONCRETE

- Definition:

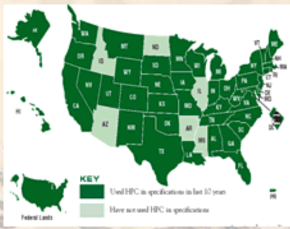
  The American Concrete Institute (ACI) defines high-performance concrete as concrete in which certain characteristics are developed for a particular application and environment. The characteristics may be considered critical for an application, cannot always be achieved routinely when using conventional constituents and normal mixing, placing and curing practices.

HIGH PERFORMANE CONCRETE - EXAMPLES

- High workability concrete
- Self compacting concrete (SCC)
- Foamed concrete
- High strength concrete
- Lightweight concrete
- No-fines concrete
- Pumped concrete
- Sprayed concrete
- Waterproof concrete
- Autoclaved aerated concrete
- Roller compacted

HIGH PERFORMANCE CONCRETE FOR HIGHWAY CONSTRUCTION

- In 1987, FHWA and AASHTO started HPC research projects
- In September 1996, formed "Lead State Teams *for HPC Implementation*" consisting of 5 states (Missouri, Nebraska, New Hampshire, Texas and Virginia)
- 1998, FHWA launched an Innovative Bridge Research and Construction Program



FHWA HIGH PERFORMANCE CONCRETE GRADATION

Performance Characteristic[2]	Standard Test Method	FHWA HPC Performance Grade[3]				
		1	2	3	4	N/A
Freeze/Thaw Durability[4] (*x* = relative dynamic modulus of elasticity after 300 cycles)	AASHTO T 161 ASTM C 666Proc. A	60% ⩽ x ⩽ 80%	80% ⩽ x			
Scaling Resistance[5] (*x* = visual rating of the surface after 50 cycles)	ASTM C 672	x = 4,5	x = 2,3	x = 0,1		
Abrasion Resistance[6] (*x* = avg. depth of wear in mm)	ASTM C 944	2.0 > x ⩾ 1.0	1.0 > x ⩾ 0.5	0.5 > x		
Chloride Permeability[7] (*x* = coulombs)	AASHTO T 277 ASTM C 1202	3000 ⩾ x > 2000	2000 ⩾ x > 800	800 ⩾ x		
Strength (*x* = compressive strength)	AASHTO T 22 ASTM C39	41 ⩽ x < 55 MPa (6 ⩽ x < 8 ksi)	55 ⩽ x < 69 MPa (8 ⩽ x < 10 ksi)	69 ⩽ x < 97 MPa (10 ⩽ x < 14 ksi)	x ⩾ 97 MPa (x ⩾ 14 ksi)	
Elasticity[10] (*x* = modulus of elasticity)	ASTM C 469	24 ⩽ x < 40 GPa (4 ⩽ x < 6 x 10^6 psi)	40 ⩽ x 50 GPa (6 ⩽ x < 7.5 x 10^6 psi)	x ⩾ 50 GPA (x ⩾ 7.5 x 10^6 psi)		
Shrinkage[8] (*x* = microstrain)	ASTM C 157	800 > x ⩾ 600	600 > x ⩾ 400	400 > x		
Creep[9] (*x* = microstrain/pressure unit)	ASTM C 512	()	()	()	()	

DETAILS OF TEST METHODS FOR DETERMINING HPC PERFORMANCE GRADES

Performance Characteristic	Standard Test Method	Notes[1]
Freeze/Thaw Durability	AASHTO T 161 ASTM C 666 Proc. A	1. Test specimen 76.2 x 76.2 x 279.4 mm (3 x 3 x 11 in) cast or cut from 152.4 x 304.8 mm (6 x 12 in) cylinder 2. Acoustically measure dynamic modulus until 300 cycles.
Scaling Resistance	ASTM C 672	1. Test specimen to have a surface area of 46,451 mm^2 (72 in^2). 2. Perform visual inspection after 50 cycles
Abrasion		1. Concrete shall be tested at 3 different locations. 2. At each location, 98 Newtons, for three, 2 minute, abrasion periods shall be applied for a total of 6 minutes of abrasion time per location. 3. The depth of abrasion shall be determined per ASTM C 799 Procedure B.
Chloride Permeability	AASHTO T 277 ASTM C 1202	1. Test per standard test method.
Strength	AASHTO T 22 ASTM C39	1. Molds shall be rigid metal or one time use rigid plastic. 2. Cylinders shall be 100 mm dia. x200 mm long (3.9 x 7.8 in) or 150 mm dia. x300 mm long (5.9 x 11.2 in). 3. Ends shall be capped with high strength capping compound, ground parallel, or placed onto neoprene pads per AASHTO specifications for Concretes 4. Use of neoprene pads on early age testing of concrete exceeding 70 Mpa at 56 days should use neoprene pads on the 56 day tests 5. The 56 day strength is recommend
Elasticity	ASTM C 469	1. Test per standard test method.
Shrinkage	ASTM C 157	1. Use 76.2 x 76.2 x 285 mm (3 x 3 11 1/4 in) specimens 2. Shrinkage measurements are to start 28 days after moist curing and be taken for a drying period of 180 days.
Creep	ASTM C 512	1. Use 152 x 305 mm (6 x 12 in) specimens 2. Cure specimens at 73° F and 50% RH after 7 days until loading at 28 days. 3. Creep measurements to be taken for a creep loading period of 180 days.

SELF-CONSOLIDATING CONCRETE

International Conferences on SCC

Beijing, China June 5-7, 2009 http://scc2009.hnu.cn

SELF-CONSOLIDATING CONCRETE

A concrete which can be placed and consolidated under its own weight without any vibration effort, and which is, at the same time, cohesive enough to be handled with acceptable segregation or bleeding.

Since the use of SCC eliminates vibration, it can have many technical, economical and environmental advantages over conventional concrete.



ADVANTAGES OF SCC

- Eliminating the need for vibration;
- Decreasing the construction time and labor cost;
- Reducing the noise pollution;
- Improving the filling capacity of highly congested structural members;
- Improving the interfacial transitional zone between cement paste and aggregate or reinforcement,
- Decreasing the permeability and improving durability of concrete, and
- Facilitating constructibility and ensuring good structural performance.

DISADVANTAGES OF SCC

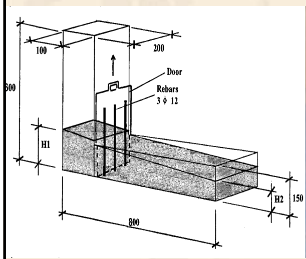
- Higher autogenous shrinkage;
- Lower stability of air voids;
- Higher portion of large air bubbles;
- Higher deformation (shrinkage and creep)
- Higher materials cost

TESTING OF SCC

- Slump Flow
- L-Box
- V-Funnel
- J-ring
- Filling Capacity
- Segregation Index

SLUMP CONE FLOW TEST

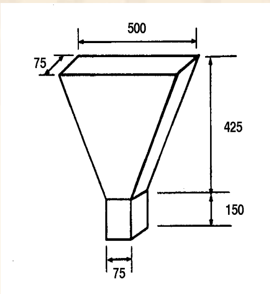
L-BOX FLOW TEST



General Acceptance Criteria For Self-consolidating Concrete

Test Method	Unit	Typical Range	
		minimum	maximum
Slump Flow	mm	500	800
L-box, H_2/H_1	Ratio	0.8	1.0
V-funnel	Sec	3	12

V-FUNNEL FLOW TEST

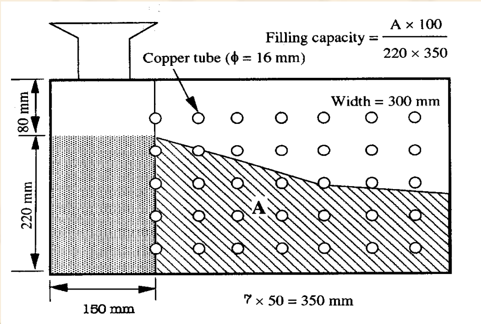


J-Ring Test

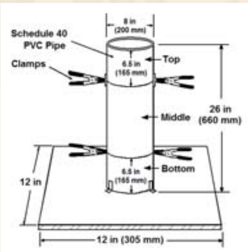
Passing Ability Rating

Difference between J-Ring Flow and Slump Flow (mm)	Passing Ability Rating	Remarks
0 – 25	0	High Passing Ability
25 - 50	1	Moderate Passing Ability
> 50	2	Low Passing Ability

FILLING CAPACITY TESTING



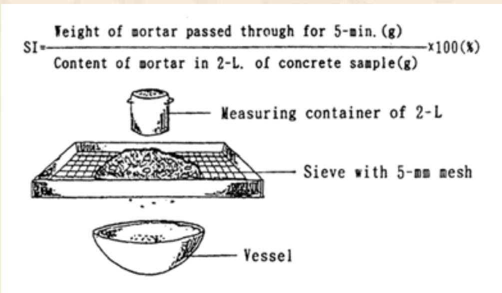
SEGREGATION TESTING (I)



$S\ \% = [(CA_B - CA_T)/((CA_B+CA_T)/2)] * 100$

- where:
- S = static segregation percent
- CA_T = mass of coarse aggregate in the top section of the column
- CA_B = mass of coarse aggregate in the bottom section of the column

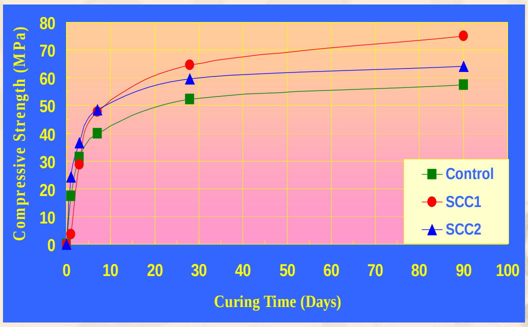
SEGREGATION TESTING (II)



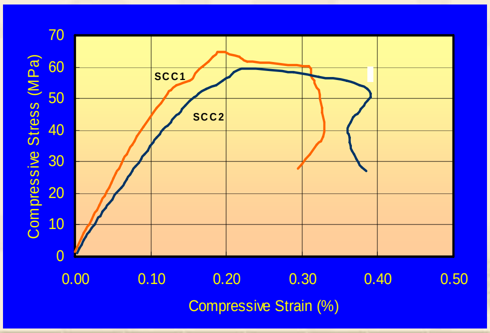
Comparisons Between

Conventional Concrete and SCC

STRENGTH DEVELOPMENT OF SCCs AND CONVENTIONAL CONCRETE



STRESS-STRAIN RELATIONSHIP OF SCCs



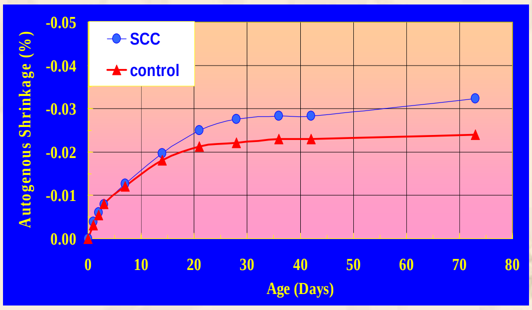
MODULUS OF ELASTICITY OF SCCs

Concrete	Modulus of Elasticity (GPa)	
	From Stress-Strain Curve	ACI 318 Equation
SCC 1	48.38	38.01
SCC 2	35.78	36.48

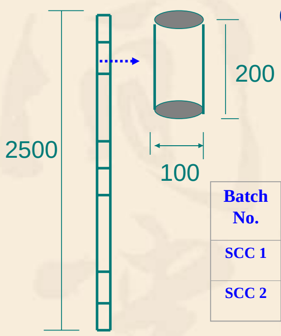
ACI 318 – relationship between modulus of elasticity E_c and compressive strength f_c:

$$E_c = 4.73 f_c^{0.5}$$

AUTOGENOUS SHRINKAGE OF SCCs AND CONVENTIONAL CONCRETE



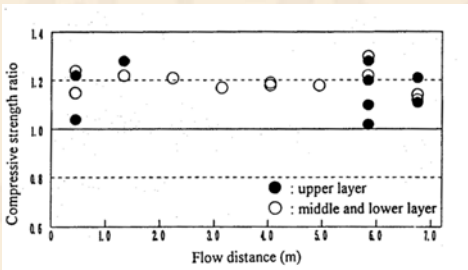
COLUMN TESTING



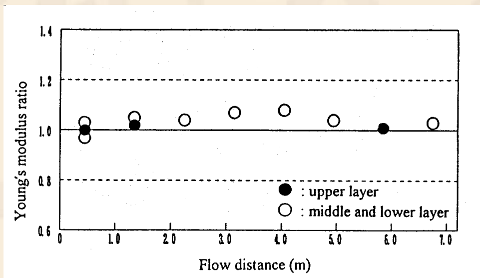
Batch No.	Strength (MPa)		Density (kg/m³)	
	Top	Bottom	Top	Bottom
SCC 1	62.0	63.3	2376	2385
SCC 2	50.8	52.6	2377	2412

TOP PARTS OF THE COLUMNS

Strength Uniformity of Concrete at Different Distances

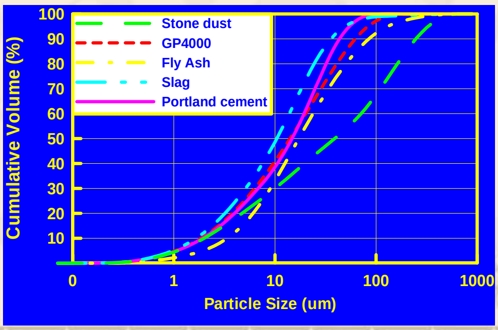


Uniformity of Young's Modulus of Concrete at Different Distances



EFFECT OF DIFFERENT POWDERS ON PROPERTIES OF SCC

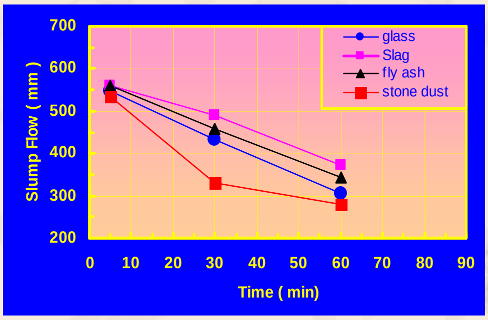
PARTICLE SIZE DISTRIBUTION OF POWDERS



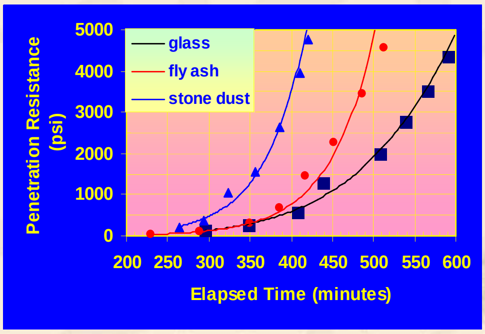
PROPERTIES OF FRESH SCCs

Powder	Slump Flow (mm)	L-box H2/H1 (%)	L-box Flow (s)	Air Content (%)	Density (kg/m^3)
Glass	550	38	8.4	2.3	2311
Fly ash	560	69	3.1	2.2	2326
Slag	560	45	5.3	2.8	2350
Stone Dust	540	25	5.8	2.9	2304

SLUMP CONE FLOWABILITY OF SCCs



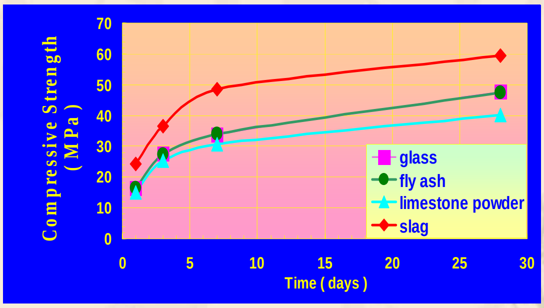
PENETRATION RESISTANCE OF SCCs



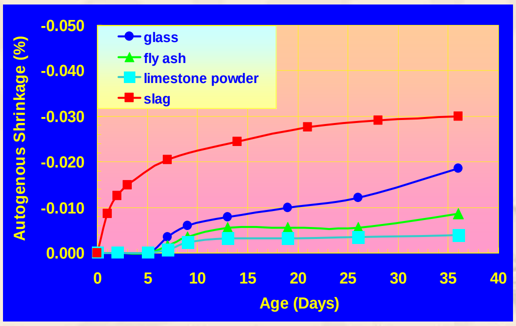
TIMES OF SETTING OF SCCs

Powder	Initial (h:m)	Final (h:m)
glass	6:25	9:35
fly ash	6:15	8:10
limestone powder	5:00	6:50

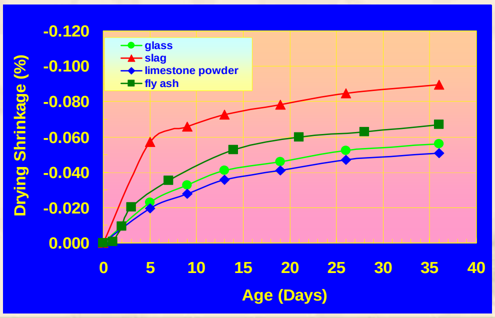
STRENGTH DEVELOPMENT OF SCCs



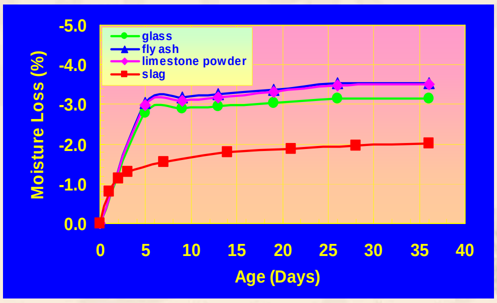
AUTOGENOUS SHRINKAGE OF SCCs



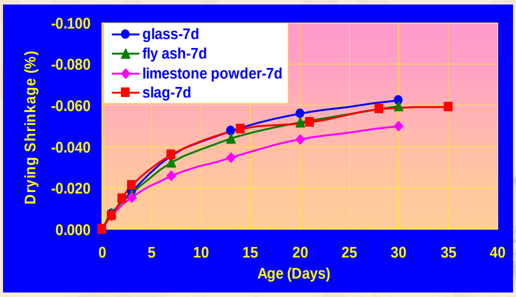
DRYING SHRINKAGE OF SCCs
AFTER ONE DAY OF MOISTURE CURING



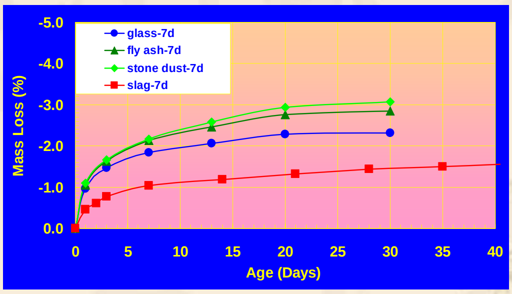
MOISURE LOSS DURING DRYING SHRINKAGE TESTING AFTER ONE DAY OF MOSIT CURING



DRYING SHRINKAGE OF SCCs AFTER SEVEN DAYS OF MOISTURE CURING



MOISTURE LOSS DURING DRYING SHRINKAGE TESTING AFTER SEVEN DAYS OF MOSIT CURING



INSULATING CONCRETE FORM (ICF) SYSTEM

- Insulating concrete form (ICF) technology uses hollow expanded polystyrene blocks or panels held together by ties as forms and place concrete inside of these forms.
- When the concrete hardens, the expanded polystyrene forms remain in place to serve as insulation and attachment points for interior and exterior finishes.

ADVANTAGES OF ICF SYSTEM

- Energy Saving - 25% to 50% energy savings of ICF versus wood or steel-framed homes;
- Greater Comfort;
- Solid & Lasting Security;
- Peace & Quiet - ICF walls allowed less than one-third as much sound to pass through;
- Less Repair & Maintenance;
- A Healthier Home & Environment.

CURRENT CONCRETE AND CONSTRUCTION FOR ICFS

- Conventional concrete with slump < 10 cm (4”)
- Place concrete every 4’ high
- Honeycombs often occur, especially around plastic form ties and rebars inside the forms.

SELF-CONSOLIDATING LIGHTWEIGHT CONCRETE (SCLC) FOR ICFS

- Self-consolidating
- Reduced density
- Increased casting height
- Enhanced thermal insulation
- Reduced foundation requirement
- Higher materials costs but lower total construction costs

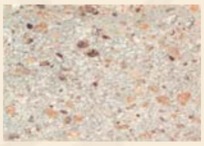
Pouring SCLC into Insulated Concrete Forms From a Concrete Truck

Exposed Hardened SCLC at the Wall End

Lightweight Concrete

Production of Lightweight Concrete

- **Air Bubbles in Aggregates**
  - **Synthetic lightweight aggregate**
  - **Natural lightweight aggregate**



- **Air Bubbles in Paste**
  - **Gas-forming method**
  - **Foaming method**

Advantages of Lightweight Concrete

- **Good performance and durability**
- **Less dead load (reduced member size, seismic inertial mass and foundation forces)**
- **Better insulation property**
- **Higher materials costs but lower total construction costs**

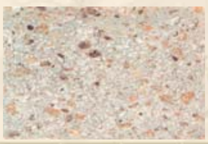
Raw Materials For Lightweight Concrete

- ASTM Type III portland cement
- Ground blast furnace slag and ASTM Class F coal fly ash
- Expanded shales as aggregates
- Gas-forming agent, foaming agent
- Polycarboxylate superplasticizer
- Polyproplene and nylon fibers

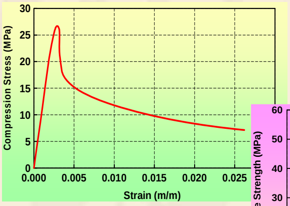
Concrete Mixture Design, Curing and Testing

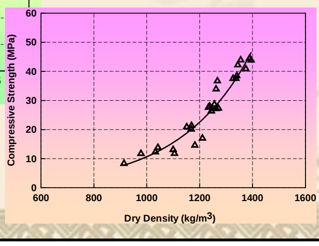
- Mixtures designed based on strength and density requirement;
- A variety of specimens and products cast;
- Used both steam curing and fog curing;
- Specimens and products tested in both small and large scale

Compression testing of Fiber-reinforced Lightweight Concrete

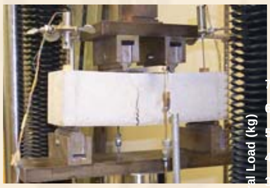


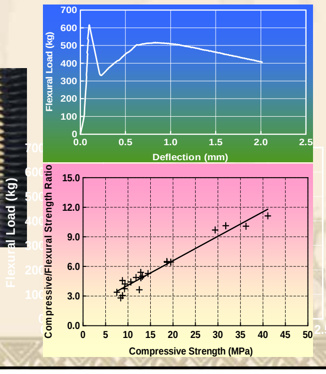
Compressive Strength, Strain and Densities of Fiber-reinforced Lightweight Concrete





Flexural testing of Fiber-reinforced Lightweight Concrete





Drilling and Nailing of Fiber-reinforced Lightweight Concrete

Saw-cutting of Fiber-reinforced Lightweight Concrete

ULTRA-LIGHTWEIGHT HIGH STRENGTH CONCRETE

Fresh Concrete		Hardened Concrete					
					Compressive Strength (psi)		
Slump (inch)	Density (lb/pcf)	Wet Density (lb/pcf)	Air-Dry Density (lb/pcf)	Oven-Dry Density (lb/pcf)	After Steam Curing	7 days	28 days
8	98	97	91	78	3800	5200	6500

Flexural Testing of Sandwich Fiber-reinforced Lightweight Concrete Panels

Central Compression Load Testing of Sandwich Fiber-reinforced Lightweight Concrete Panels

Production of Fiber-reinforced Lightweight Concrete Panels

A House Built With Fiber-reinforced Lightweight Concrete Panels

Durability of Concrete Materials and Structures

Main Concrete Durability Problems

- Corrosion of steel in concrete
- Freezing-thawing cycles
- Alkali-aggregate reaction (AAR)
- Sulphate attack

Alkali-reactive Aggregate Distribution in China

Chloride Corrosion in Reinforced Concrete

- Repair cost of existing damaged concrete structures costs thousand millions in America;
- 80% damage of reinforced concrete structure associates with corrosion of the steel;
- Resource of chloride: deicing & salt seawater.

Hunan University

Durability Design of Concrete Materials and Structures

《Code for durability design of concrete structures》

《混凝土结构耐久性设计规范》

GB/T50476-2008，

Became effective since May 1, 2009

Hangzhou Bay Bridge

It is the first project in China designed based on this guide.

Main tower

Hangzhou Bay Bridge

- A **36 km** long bridge across Hangzhou Bay in Zhejiang Province, east coast of China.
- There is severe aggressive environment due to high Cl^- concentration in seawater and soil.
- The designed service life is **100 year**. Corrosion of reinforcement should not occur in this period.

Durable marine concrete

- The controlling factor of concrete durability is Cl^- ion diffusion efficiency.
- High volume mineral admixture concrete with low water-binder ratio was adopted to lower Cl^- ion diffusion coefficient of concrete.

Properties of raw materials

- **Cement**: PII-42.5, 3d strength 32.0MPa, 28d strength 52.8MPa.
- **Fly ash**: low-Ca type, LOI=3.5%, water demand=91%, SO_3=0.68%, 0.045mm sieve residue=9.1%
- **GGBS**: activity factor=116%, SSA=446 m^2/kg
- **Aggregate**: 5-25 mm, Non AAR activity
- **Sand**: river sand, fineness module 2.6
- **Superplasticizer**: Naphthaline-type for ready-mixing concrete, polycarboxylate-type for precasting concrete

Concrete mix

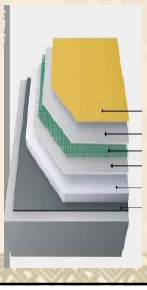
	Strength grade	W/b	Cement (kg/m^3)	Fly ash (kg/m^3)	GGBS (kg/m^3)
Foundation inland	C25	0.36	165	124	124
Foundation under water	C30	0.31	264	216	
Pier	C40	0.35	162	162	81
Box girder	C50	0.32	212	47	212

Requirement on Cl^- ion penetrativity of concrete determined by RCM method

Structure section	Cl^- ion diffusion coefficient of concrete / $x10^{-12}$ m^2/s
Pouring pile	≤3.0
Foundation	≤2.5
Pier	≤2.5
Box girder	≤1.5
Tower	≤1.5

Thermal Insulation of Concrete Structures

Thermally Insulation System I



Thermally Insulation System II

1. Brick Wall
2. Bonding Mortar
3. EPS Board
4. Siding

Insulating EPS Board and Water Protection (WP) Protection Mortar

Performance Requirements for WP Mortar

(Beijing standard)

PERFORMANCE		REQUIREMENT	CURING AND TESTING CONDITIONS
Bonding strength with cement mortar (MPa)	Standard curing	⩾0.70	14 d of standard curing
	Resistance to temperature change	⩾ 0.50	After 7 d of standard curing, then in an oven at 70±2℃ for 24 h and in room for 3 to 6 h
	Water resistance	⩾ 0.50	After 14 d of standard curing, then in water at 20±2℃ for 48 h
	Freezing-thawing resistance	⩾ 0.50	After 14 d of standard curing, then 25 freezing-thawing cycle
Bonding strength with EPS board (MPa)	standard curing	⩾0.10 or EPS destroyed	14 d of standard curing
	Water resistance	⩾ 0.10 or EPS destroyed	After 14 d of standard curing then in water at 20±2℃ for 48 h
	Freezing-thawing resistance	⩾ 0.10 or EPS destroyed	After 14 d of standard curing then 25 freezing-thawing cycles
Operational time (h)		⩾ 2	
24 h water absorption, g/m²		⩽1000	After 28 d of standard curing then in water at 20±1℃ for 24 h
Compressive/flexural strength ratio		⩽3.0	28 d of standard curing
Cracking resistance		no cracking	28 d of standard curing
Water permeability (24 h) (ml)		⩽3.0	28 d of standard curing then tested for 24 h

Smart Self-Repairing Barrier

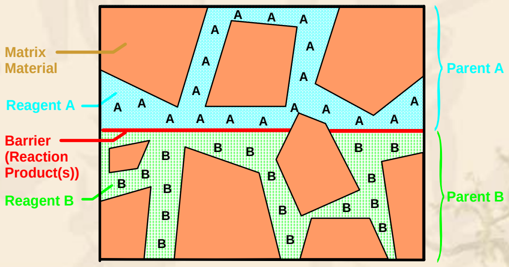
APPLICATIONS OF BARRIERS IN GEOENVIRONMENTAL ENGINEERING

- Landfill Liners and Covers
- Mining Waste Liners and Covers
- Hazardous Waste Containment Liners
- Vertical Walls
- Covers for Contaminated Sites

COMMON ENGINEERING BARRIERS

- Clayey Barriers
- Geomembranes
- Geosynthetic/Clay Composites
- Bentonite Based Barriers
- Hydraulic Cement Based Barriers (Portland Cement Pastes, Soil Cement, Lime-Pozzolan Blends, Lime-Slag Blends, Concrete, Polymer Concrete)
- Asphalt
- Chemical Barriers (silicates, lignosulfites, phenoplasts, aminoplasts, etc..)

SMART SELF-REPAIRING BARRIER SYSTEM

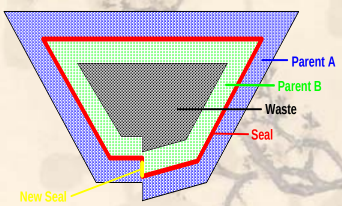


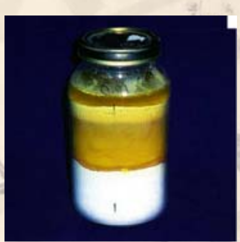
CHEMICAL REACTION FOR THE FORMATION OF A SEAL

A + B → Reaction Product(s)

(Interface) (Impermeable Seal)

SCHEMATIC ILLUSTRATION OF SELF-REPAIRING OF THE BARRIER





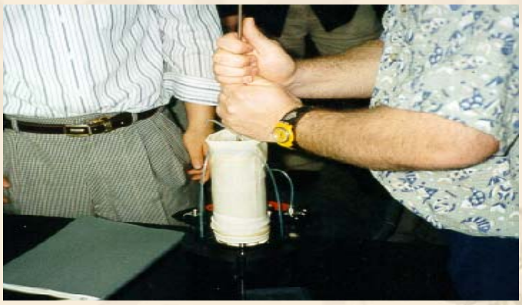
HYDRAULIC CONDUCTIVITY

$$k = \frac{L}{t} \cdot \frac{a}{A} \ln \frac{h_1}{h_2}$$

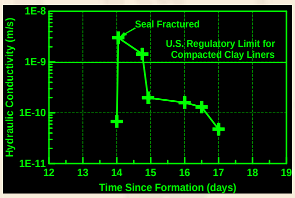
Where:

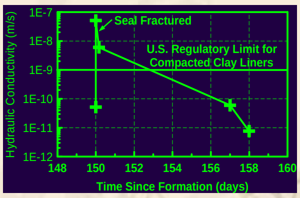
k = hydraulic conductivity, m/s;
L = length of the sample, m
t = testing time period; s
a = cross-sectional area of standpipe, m^2;
A = cross-sectional area of the sample, m^2;
h_1 = initial water level in the standpipe, m; and
h_2 = final water level in the standpipe after the testing, m

FRACTURE OF THE SEAL



LABORATORY TESTING OF SMART SELF-REPAIRING LINER

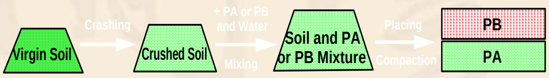




FIELD TESTING PROGRAM

- Construction Quality Assurance/Quality Control
  - Moisture Content
  - Particle Size Distribution
  - Uniformity of Mixing
  - Dosage of Reactant
  - Compaction Degree
- Field Cores
  - Compressive Strength
  - Hydraulic Conductivity
- In-situ Self-healing Testing
  - Sealed Single Ring Infiltration (SSRI)

CONSTRUCTION AND QA/QC PROGRAM FOR LINER INSTALLATION



Moisture content
Bulk density
Degree

Moisture Content
Bulk Density

Moisture Content
Bulk Density

Dosage of Reagent
Particle Size
Compaction Test

Moisture Content
Compaction

MIXING OF RAW MATERIALS

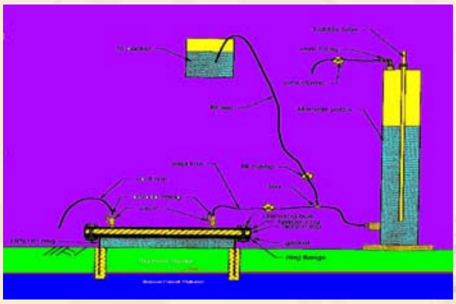
SPREAD AND COMPACTION OF MIXED MATERIALS

QUALITY TEST OF COMPACTED MATERIALS

DIGGING TRENCH

CONSTRUCTION SITE

ILLUSTRATION OF FIELD SSRI TESTING



SSRI

SSRI TESTING SETUP

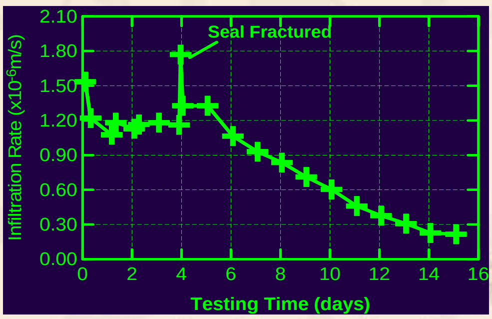
INFILTRATION RATE

$$I = \frac{Q}{t.A} x10^{-6}$$

Where:

I = infiltration rate, m/s;
Q = volume of water flow, mL;
t = time period of water flow, s; and
A = cross-sectional area of the ring, m^2.

FIELD SSRI TESTING RESULTS



CORING OF FIELD SAMPLES

RESULTS FROM FIELD CORES

- **Compressive Strength after 28 days**
  - **Parent A** **0.82 MPa**
  - **Parent B** **1.13 MPa**
- **Hydraulic Conductivity**
  - **Seal (~3 mm at 28 days)** **3.5×10^{-11} m/s**

EXAMINATION OF THE SEAL ON THE SITE


THANK YOU!
Questions?