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Dimensional Stability of Concrete

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Introduction

Dimensional changes of concrete:

- Elastic deformation
- Creep deformation

} Relates to the applied loadings

- Thermal expansion / contraction
- Swelling / shrinkage

} Relates to the materials and environmental factors

Problems caused by dimensional changes:

- Excessive deflections
- Cracking ⇒ Adversely affecting the aesthetics, water tightness, structural integrity and durability of structures

Introduction

Dimensional changes of concrete:

- Elastic deformation
- Creep deformation

} To be dealt with from the structural design perspective

- Thermal expansion / contraction
- Swelling / shrinkage

} To be dealt with from the concrete mix design perspective

Early thermal cracking and shrinkage cracking account for the majority of cracking phenomena in concrete structures

Introduction

Early thermal cracking:

- During curing, heat is generated from the chemical reactions of cementitious materials
- Temperature of curing concrete increases
- Heat dissipates in subsequence and causes the temperature to decrease eventually to the ambient
- Cracking may result if the thermal movement is restrained

Alleviation measures of early thermal cracking:

- Reduce the heat generation of concrete
- Apply internal cooling to the concrete
- Apply external heat insulation
- Add crack control steel

Introduction

Shrinkage cracking:

- Mainly due to drying shrinkage
- Water gradually evaporates from concrete and leads to reduction in volume
- Cracking may result if the shrinkage movement is restrained

Alleviation measures of shrinkage cracking:

- Reduce the drying shrinkage of concrete mix
- Provide movement joints
- Provide late cast strips
- Add crack control steel

Introduction

Reduction of heat generation of concrete:

- Reducing the cementitious paste volume
- Adding supplementary cementitious materials
  - Fly ash (FA)
  - Silica fume (SF)
  - Ground granulated blastfurnace slag (GGBS)
- Adding inert filler
  - Limestone fines (LF)

Reduction of drying shrinkage of concrete:

- Reducing the cementitious paste volume
- Adding inert filler
  - Limestone fines (LF)
- Pretreating rock aggregates to reduce water absorption
  - Polymer latex
  - Water repellent

Introduction

Addition of inert filler - filler technology:

- Inert filler (e.g. limestone fines) is not cementitious
- Addition in large quantity to replace cement would increase the W/C ratio and adversely affect strength
- It is advocated to add filler to replace an equal volume of cementitious paste without changing the water/cementitious materials (W/CM) ratio
- Filler can fill into voids between aggregate particles so as to reduce the cementitious paste volume required to fill up those voids
- Addition of filler allows the reduction of cementitious paste volume

Experimental Programme

Materials:

- Strength class 52.5N ordinary Portland cement
- Low-calcium FA
- Undensified condensed SF
- Finely ground LF
- Crushed granite coarse aggregate (20 mm maximum size)
- Crushed granite fine aggregate (5 mm maximum size)
- Aqueuous polycarboxylate type superplasticizer (SP)
- Polymer latex solution
- Water repellent solution

Experimental Programme

Concrete mix design:

- The LF content is measured by volume as a percentage of total volume of concrete
- The FA and SF contents are measured by mass as a percentage of total cementitious materials
- 21 concrete mixes for experimentation of heat generation
  - W/CM = 0.40, 0.45, 0.50
  - LF = 0, 4, 8%
  - FA = 0, 40%
  - SF = 0, 10%
  - Powder paste volume = 34%
- 20 concrete mixes for experimentation of shrinkage
  - W/C = 0.35, 0.40, 0.45, 0.50, 0.55, 0.60
  - LF = 0, 4, 8% for W/C $\leq$ 0.50; LF = 0, 4, 8, 12% for W/C $\geq$ 0.55
  - Powder paste volume = 34%
- 6 concrete mixes for experimentation of aggregate treatment
  - W/C = 0.48
  - Paste volume = 30%

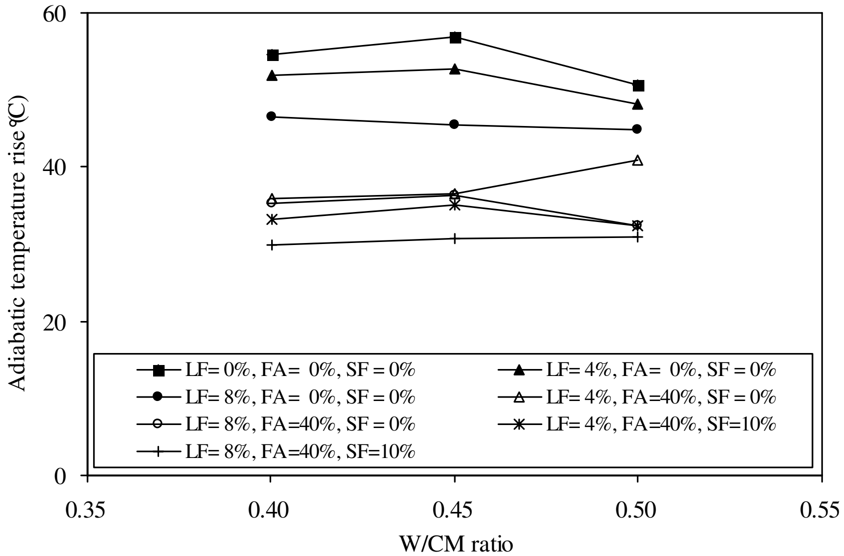
Experimental Findings on Heat Generation

Mix no. (W/CM LF FA SF)	SP dosage, % by weight of powder content	Slump, mm	Flow, mm	7 day cube strength, MPa	28 day cube strength, MPa
0.40-0-0-0	0.98	225	530	65.2	74.8
0.45-0-0-0	0.78	230	501	52.0	63.8
0.50-0-0-0	0.89	230	569	47.0	56.0
0.40-4-0-0	1.23	245	555	70.8	80.5
0.45-4-0-0	1.04	253	678	60.7	67.6
0.50-4-0-0	0.98	235	575	53.5	62.0
0.40-8-0-0	1.94	255	679	74.1	85.1
0.45-8-0-0	1.74	245	728	65.2	76.0
0.50-8-0-0	1.57	255	733	58.8	68.7
0.40-4-40-0	1.21	260	663	40.1	60.6
0.45-4-40-0	0.79	260	648	32.5	50.4
0.50-4-40-0	0.49	240	678	27.0	45.9
0.40-8-40-0	0.61	255	745	42.6	61.5
0.45-8-40-0	0.74	270	600	35.7	56.8
0.50-8-40-0	0.74	275	708	29.0	45.5
0.40-4-40-10	1.94	270	725	38.3	66.8
0.45-4-40-10	0.99	260	698	33.4	55.1
0.50-4-40-10	1.11	250	593	27.0	48.5
0.40-8-40-10	1.21	230	533	42.3	68.9
0.45-8-40-10	1.06	255	628	36.3	61.6
0.50-8-40-10	0.81	230	538	29.5	52.4

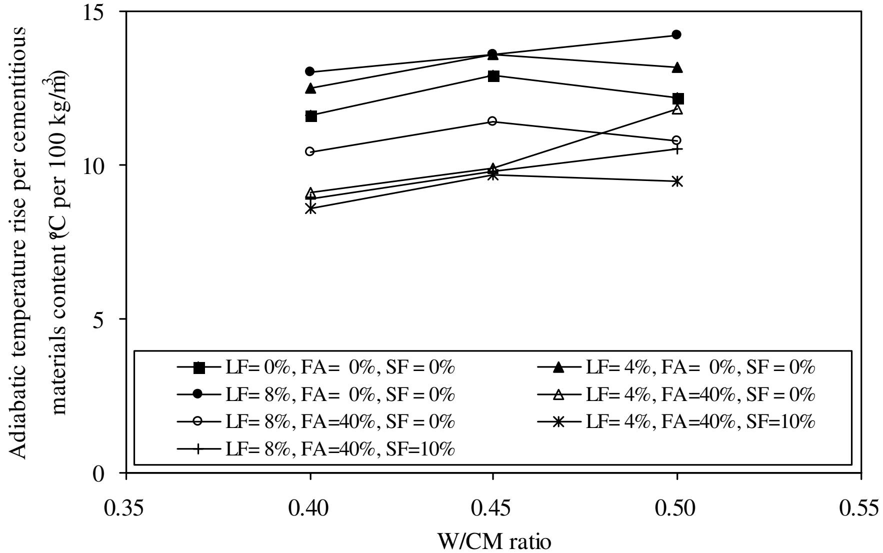
Mix no. (W/CM LF FA SF)	Measured temperature rise (before heat loss compensation), C	Adiabatic temperature rise		Heat generation	
		Temperature rise (after heat loss compensation), C	Per cementitious materials content, C/(100 kg/m³)	Per volume of concrete, MJ/m³	Per unit weight of cementitious materials, MJ/(100 kg)
0.40-0-0-0	47.3	54.5	11.6	140.1	29.8
0.45-0-0-0	47.1	56.9	12.9	147.0	33.4
0.50-0-0-0	41.7	50.6	12.2	131.4	31.8
0.40-4-0-0	44.9	52.0	12.5	130.8	31.5
0.45-4-0-0	43.9	52.7	13.6	133.3	34.4
0.50-4-0-0	41.0	48.1	13.2	122.2	33.5
0.40-8-0-0	38.9	46.6	13.0	114.8	32.0
0.45-8-0-0	37.7	45.5	13.6	112.6	33.5
0.50-8-0-0	37.1	44.9	14.2	111.5	35.4
0.40-4-40-0	26.0	35.9	9.1	87.6	22.3
0.45-4-40-0	27.0	36.6	9.9	90.0	24.4
0.50-4-40-0	30.2	41.0	11.8	101.5	29.2
0.40-8-40-0	24.2	35.3	10.4	84.7	24.9
0.45-8-40-0	26.7	36.4	11.4	87.9	27.5
0.50-8-40-0	24.1	32.4	10.8	78.6	26.1
0.40-4-40-10	25.6	33.2	8.6	80.4	20.8
0.45-4-40-10	27.4	35.0	9.7	85.3	23.6
0.50-4-40-10	24.9	32.4	9.5	79.4	23.2
0.40-8-40-10	22.1	29.9	8.9	71.2	21.3
0.45-8-40-10	22.5	30.8	9.8	73.8	23.5
0.50-8-40-10	22.2	31.0	10.5	74.7	25.2

Experimental Findings on Heat Generation

- At the same W/CM ratio, adiabatic temperature rise is generally lower at higher LF content
- At the same W/CM and LF content, adiabatic temperature rise is generally lower at higher FA content
- At the same W/CM, LF and FA contents, adiabatic temperature rise is generally lower at higher SF content



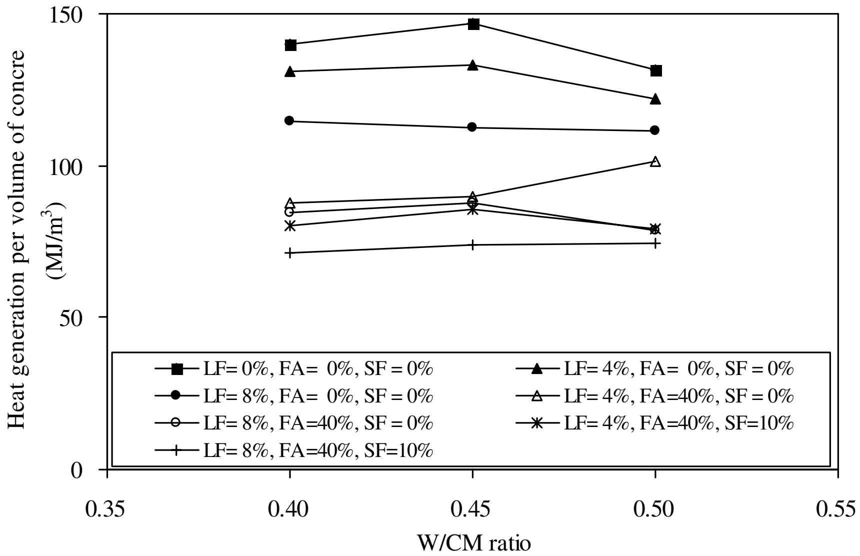
Adiabatic temperature rise



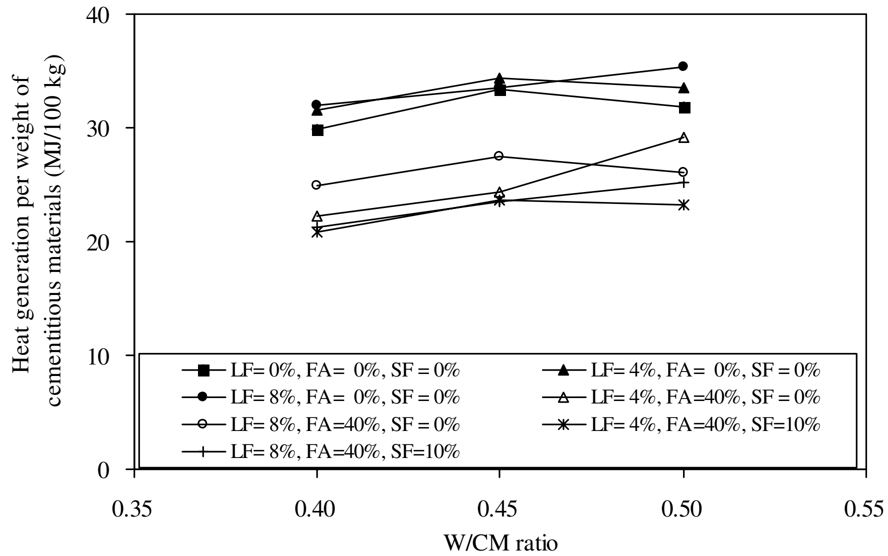
Adiabatic temperature rise per cementitious materials content

Experimental Findings on Heat Generation

- At all W/CM ratios, heat generation per volume decreases while heat generation per weight of CM increases slightly as LF content increases
- At all W/CM and LF contents, both heat generation per volume and heat generation per weight of CM decrease substantially as FA content increases
- At all W/CM, LF and FA contents, both heat generation per volume decreases while heat generation per weight of CM decrease slightly as SF content increases



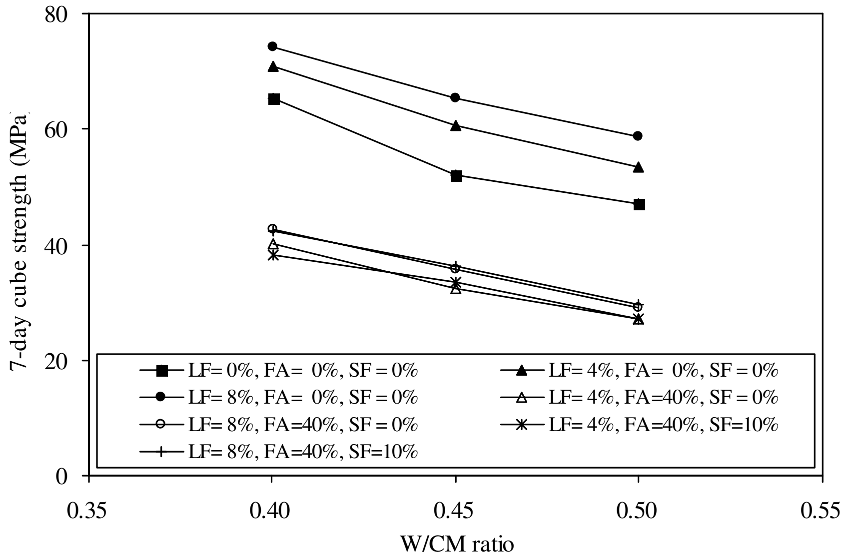
Heat generation per volume of concrete



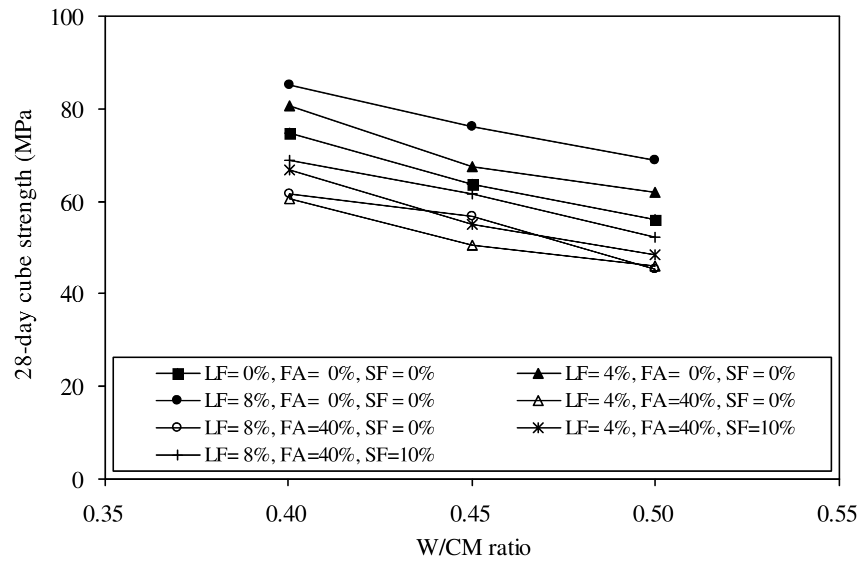
Heat generation per weight of cementitious materials

Experimental Findings on Heat Generation

- Addition of LF without changing the W/CM ratio significantly increases the 7-day and 28-day strengths
- Addition of FA without changing the W/CM ratio significantly decreases the 7-day and 28-day strengths
- Addition of SF without changing the W/CM ratio increases the 7-day and 28-day strengths



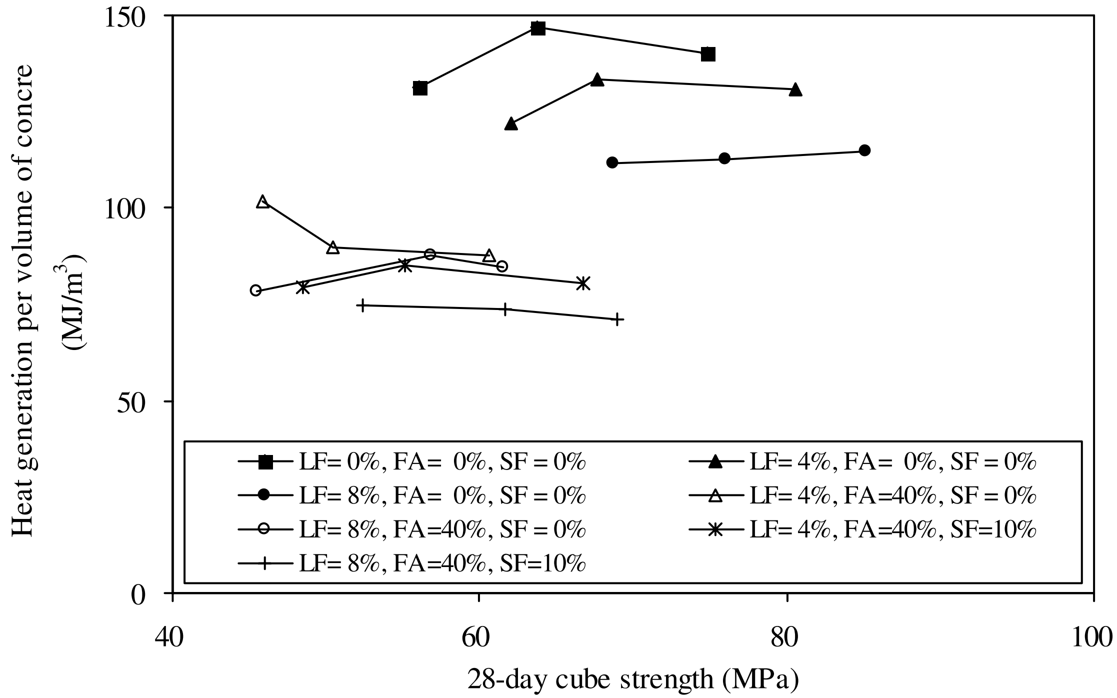
7-day cube strength



28-day cube strength

Experimental Findings on Heat Generation

- On equal strength basis, the addition of LF alone, the addition of (LF+FA), and the addition of (LF+FA+SF) have increasing effectiveness in reducing the heat generation of concrete



Concurrent heat generation per volume of concrete and cube strength

Experimental Findings on Shrinkage

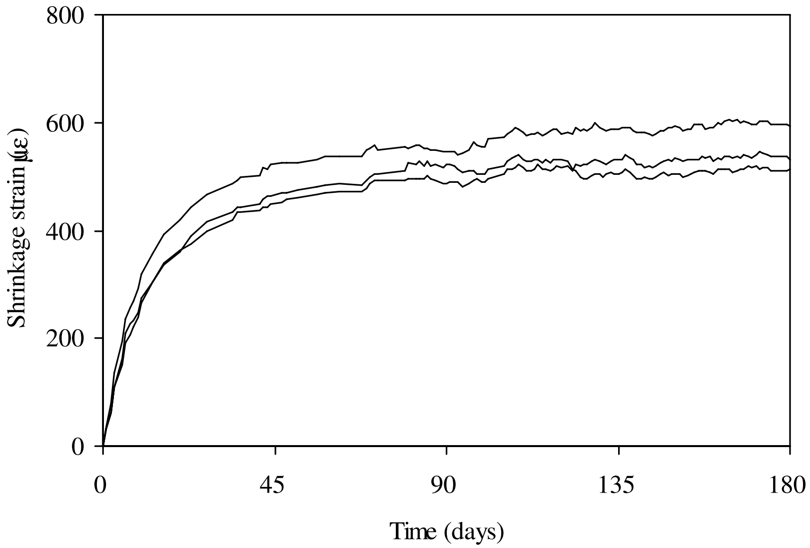
Mix no.	SP dosage, % by mass of powder	Slump, mm	Flow, mm	7 day cube strength, MPa	28 day cube strength, MPa
C-0.35-0	1.00	240	583	71.3	82.2
C-0.35-4	1.60	250	623	77.8	87.6
C-0.35-8	2.13	265	650	78.6	89.8
C-0.40-0	0.88	240	640	61.6	72.6
C-0.40-4	1.11	260	673	70.7	78.2
C-0.40-8	1.80	245	653	72.1	80.3
C-0.45-0	0.70	250	693	55.2	62.9
C-0.45-4	0.90	230	645	57.4	66.6
C-0.45-8	1.25	260	655	65.3	75.8
C-0.50-0	0.63	240	686	46.5	55.9
C-0.50-4	0.88	230	640	55.1	63.4
C-0.50-8	1.08	210	605	60.5	69.9
C-0.55-0	0.55	220	675	43.2	52.3
C-0.55-4	0.84	235	693	49.1	58.2
C-0.55-8	0.98	245	648	50.8	62.5
C-0.55-12	1.73	260	615	54.4	65.1
C-0.60-0	0.49	225	630	36.7	45.3
C-0.60-4	0.72	250	685	42.3	50.9
C-0.60-8	0.91	255	626	44.6	52.6
C-0.60-12	1.60	235	645	49.7	58.2

Experimental Findings on Shrinkage

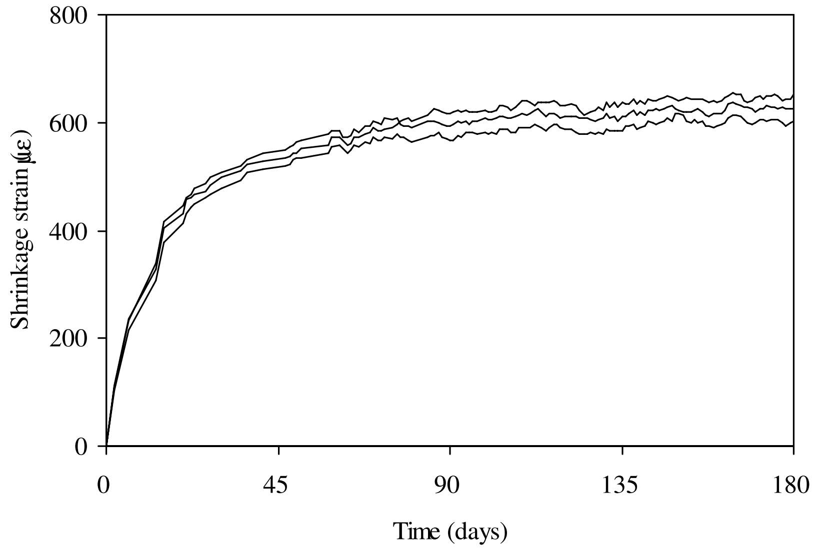
Mix no.	30 day shrinkage strain, $\mu\varepsilon$	60 day shrinkage strain, $\mu\varepsilon$	Ultimate shrinkage strain, $\mu\varepsilon$	Shrinkage half time, days
C-0.35-0	402	456	517	8.7
C-0.35-4	338	383	443	9.0
C-0.35-8	305	340	374	7.4
C-0.40-0	437	500	546	9.7
C-0.40-4	372	433	467	9.2
C-0.40-8	337	389	410	8.9
C-0.45-0	492	581	626	10.7
C-0.45-4	447	513	588	9.7
C-0.45-8	405	467	511	9.1
C-0.50-0	516	603	684	10.8
C-0.50-4	449	525	615	10.3
C-0.50-8	416	484	544	9.0
C-0.55-0	527	618	702	10.0
C-0.55-4	497	573	655	9.9
C-0.55-8	481	536	605	8.8
C-0.55-12	440	515	574	9.5
C-0.60-0	621	683	771	8.6
C-0.60-4	531	629	706	9.5
C-0.60-8	528	607	683	8.2
C-0.60-12	480	538	622	8.7

Experimental Findings on Shrinkage

- Triplicated specimens were produced and tested
- The shrinkage strains of the triplicated specimens are averaged
- The shrinkage strains are almost constant after 120 days
- The 180-day shrinkage strains are taken as the ultimate shrinkage strain
- The shrinkage half-time is determined as the time required for the shrinkage to reach half of the ultimate shrinkage



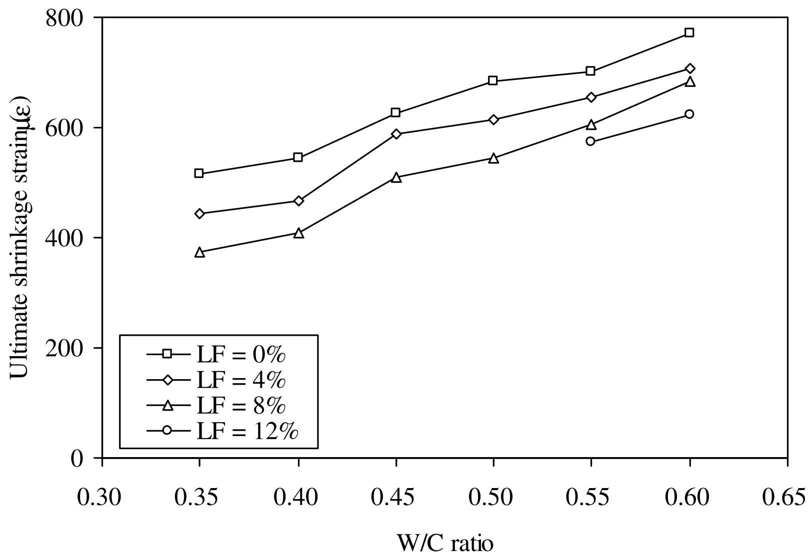
Shrinkage strain-time curves of Mix C-0.40-0



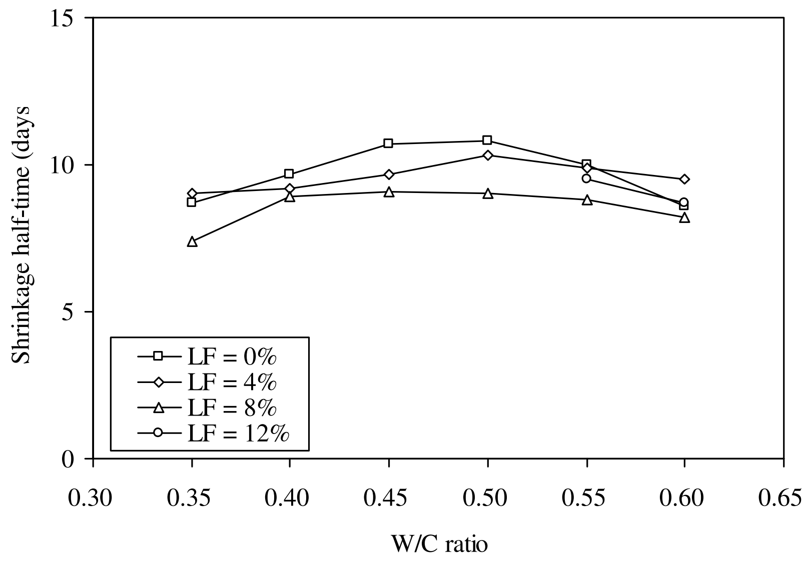
Shrinkage strain-time curves of Mix C-0.45-0

Experimental Findings on Shrinkage

- At all W/C ratios, the ultimate shrinkage strain decreases steadily and substantially as LF content increases
- At all LF contents, the ultimate shrinkage strain increases with W/C
- The shrinkage half-time varies only slightly with LF content and W/C



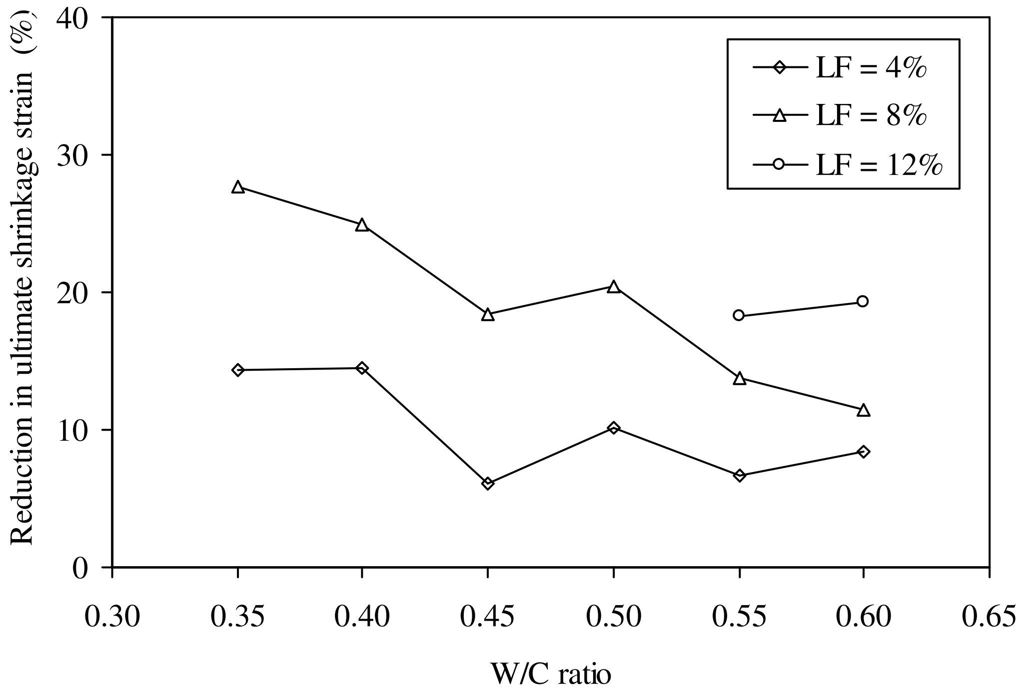
Effects of LF volume on ultimate shrinkage strain



Effects of LF volume on shrinkage half-time

Experimental Findings on Shrinkage

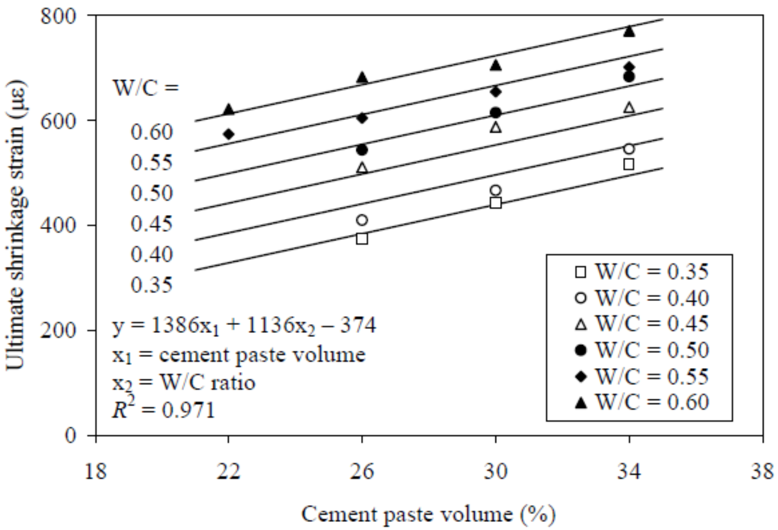
- The reduction in shrinkage strain resulted from addition of LF is generally larger at lower W/C ratio, and can amount to as much as 28%



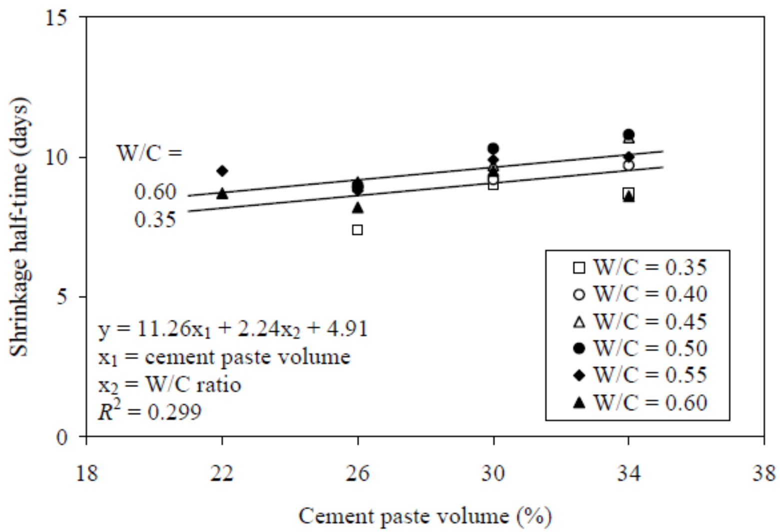
Percentage reduction in ultimate shrinkage strain due to addition of LF

Experimental Findings on Shrinkage

- The ultimate shrinkage strain is strongly related to the cement paste volume and W/C, and is generally smaller at smaller paste volume and/or lower W/C
- The shrinkage half-time is only weakly related to the cement paste volume and W/C



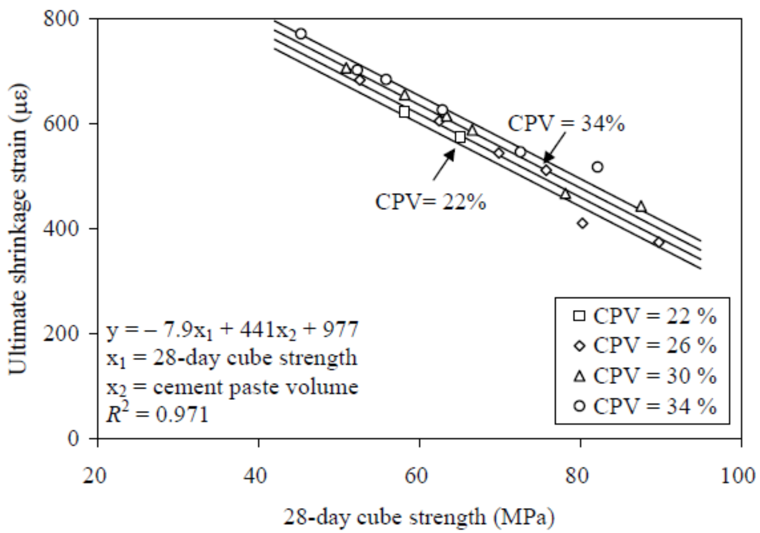
Effects of cement paste volume on ultimate shrinkage strain



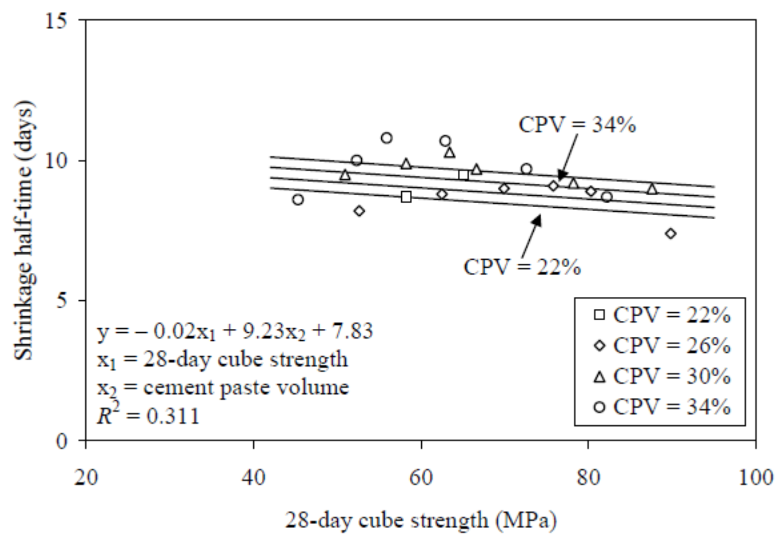
Effects of cement paste volume on shrinkage half-time

Experimental Findings on Shrinkage

- The ultimate shrinkage strain is strong related to the concrete strength and cement paste volume, and is generally smaller at higher concrete strength and/or smaller cement paste volume
- The shrinkage half-time is only weakly related to the concrete strength and cement paste volume
- On the whole, the effect of concrete strength on the ultimate shrinkage strain is larger than the effect of paste volume



Effects of concrete strength on ultimate shrinkage strain (CPV means cement paste volume)



Effects of concrete strength on shrinkage half-time (CPV means cement paste volume)

Experimental Findings on Shrinkage

Effect of aggregate treatment:

- 6 groups of aggregates with different treatment applied were used for concrete production
- Group A1: untreated and stored in the laboratory for 1 month to have their moisture condition stabilized
- Group A2: untreated but immersed in water at 27°C for 7 days to become fully saturated
- Group A3: first immersed in polymer latex (20% solution of Ronafix) for 6 hours, rinsed by clean water for 15 minutes and then dried in a condition chamber at 50°C and 50% relative humidity for 7 days
- Group A4: first immersed in water repellent (0.6% solution of Darapel) for 6 hours, rinsed by clean water for 15 minutes and then dried in a condition chamber at 50°C and 50% relative humidity for 7 days
- Group A5: mimicked Group A3 except the 6-hour immersion in polymer latex was extended to 3 days
- Group A6: mimicked Group A4 except the 6-hour immersion in water repellent was extended to 3 days

Experimental Findings on Shrinkage

Effect of aggregate treatment:

- The water absorption of aggregate decreases after treatment
- The polymer latex and water repellent are effective in filling the pores in the aggregate to hamper the ingress of water

<u>Treatment applied to aggregate and water absorption</u>

Aggregate group designation	Treatment applied	Water absorption (%)		
		Fine aggregate	10 mm aggregate	20 mm aggregate
A1	As supplied	1.54	0.95	0.76
A2	Immersion in water	1.54	0.95	0.76
A3	Immersion in Ronafix for 6 hours and then drying	1.09	0.77	0.59
A4	Immersion in Darapel for 6 hours and then drying	1.06	0.77	0.67
A5	Immersion in Ronafix for 3 days and then drying	0.91	0.76	0.62
A6	Immersion in Darapel for 3 days and then drying	0.87	0.78	0.61

Experimental Findings on Shrinkage

Effect of aggregate treatment:

- The ultimate shrinkage strains of concrete mixes made with treated aggregates are significantly smaller than those of the concrete mixes made with untreated aggregates

Mass loss and shrinkage of concrete

Aggregate group designation	Mass loss, %	Ultimate shrinkage strain, $\mu\varepsilon$	Reduction in shrinkage strain, %	Shrinkage half time, days
A1	3.09	822	-	36
A2	3.44	812	-	33
A3	3.02	712	-13.4	34
A4	3.12	717	-12.8	40
A5	2.26	599	-27.1	18
A6	2.31	653	-20.6	22
Note: Each value reported is the averaged value of the four specimens tested.				

Conclusions

- The effects of adding LF as cementitious paste replacement, adding FA and SF as cement replacement, and pretreating aggregates with polymer latex or water repellent on the workability, strength, heat generation and drying shrinkage of concrete have been studied.

- Based on the experimental results, it is advocated that the best strategy for reducing the heat generation of concrete is to add supplementary cementitious materials as cement replacement and add inert fillers as cementitious paste replacement at the same time. This strategy can reduce the heat generation by up to 50%.

- It is also advocated that the best strategy for reducing the drying shrinkage of concrete is to add inert fillers as cementitious paste replacement to reduce the paste volume, lower the W/CM ratio to increase concrete strength and if affordable also pretreat the aggregate to reduce its water absorption. This strategy can reduce the ultimate shrinkage strain down to about 400$\mu\varepsilon$ or even lower.

- With the heat generation and drying shrinkage so reduced, the dimensional stability of the concrete would be improved and the risk of non-structural cracking would be minimized.

Dimensional Stability of Concrete

Thank you!