Performance of LC^3 Concrete

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Workshops on Limestone Calcined Clay Cements
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Mixture variables

- Materials used
  - Limestone Calcined Clay Cement (LC^3)
  - OPC 53 grade cement
  - Fly ash – Class F
- Design Mixes
  - Grades M30 (residential) and M50 (infra)
  - Common mix with w/b - 0.45 and total binder - 360 kg/m^3
- Target slump: 80-120 mm

Concrete Mix Design

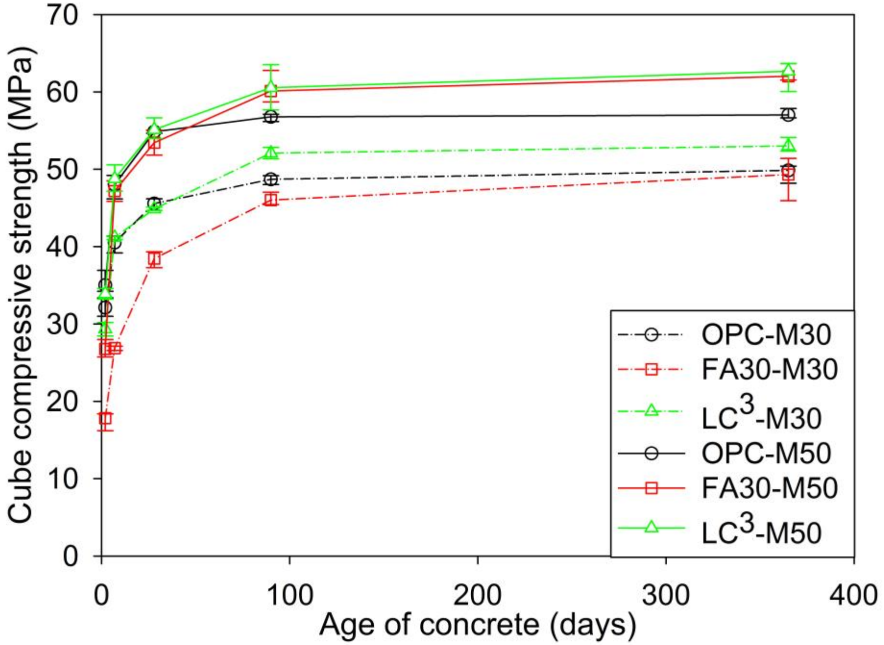
Sl. No	Mix I.D.	w/b	Cement	Fly ash	Water content	Fine aggregate	Coarse aggregate		SP dosage (% wt. of cement
			kg/m³						
1	OPC-M30	0.50	310	0	155	695	496	744	0.02
2	FA30-M30	0.45	217	93	140	723	491	737	0.65
3	LC³-M30	0.50	310	0	155	708	491	736	1.00
4	OPC-M50	0.40	360	0	144	703	477	716	0.65
5	FA30-M50	0.35	266	114	133	699	475	713	0.60
6	LC³-M50	0.40	340	0	136	704	488	732	0.85
7	OPC-C		360	0	162	721	463	694	0.10
8	FA30-C	0.45	252	108	162	721	463	694	0.23
9	LC³-C		360	0	162	721	463	694	0.36

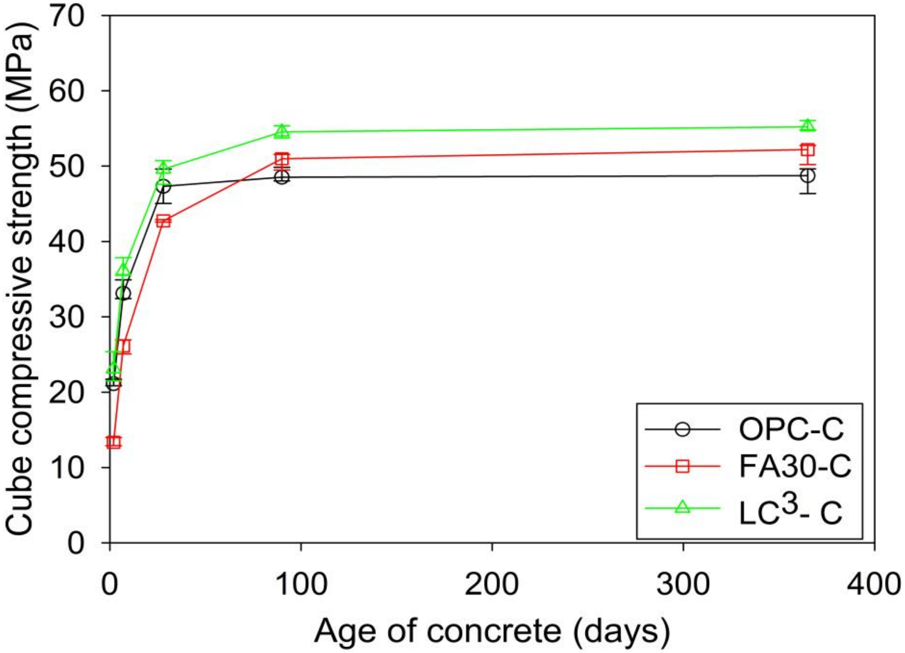
LC3 compared to OPC: Similar binder content and w/b

LC3 compared to FA30: Lower binder content and higher w/b for same grade

Higher SP requirement for LC3 concrete – expected

Evolution of compressive strength

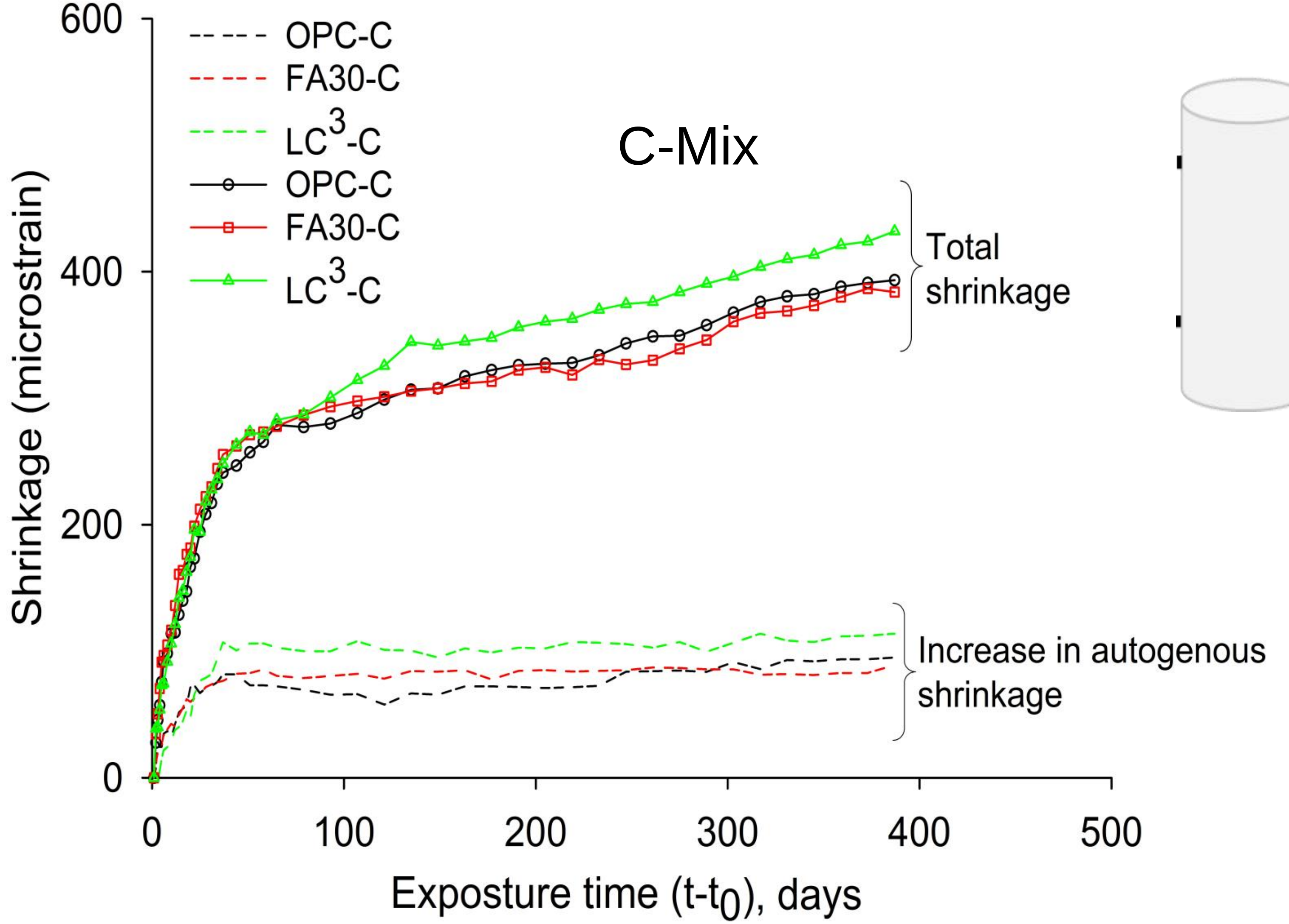




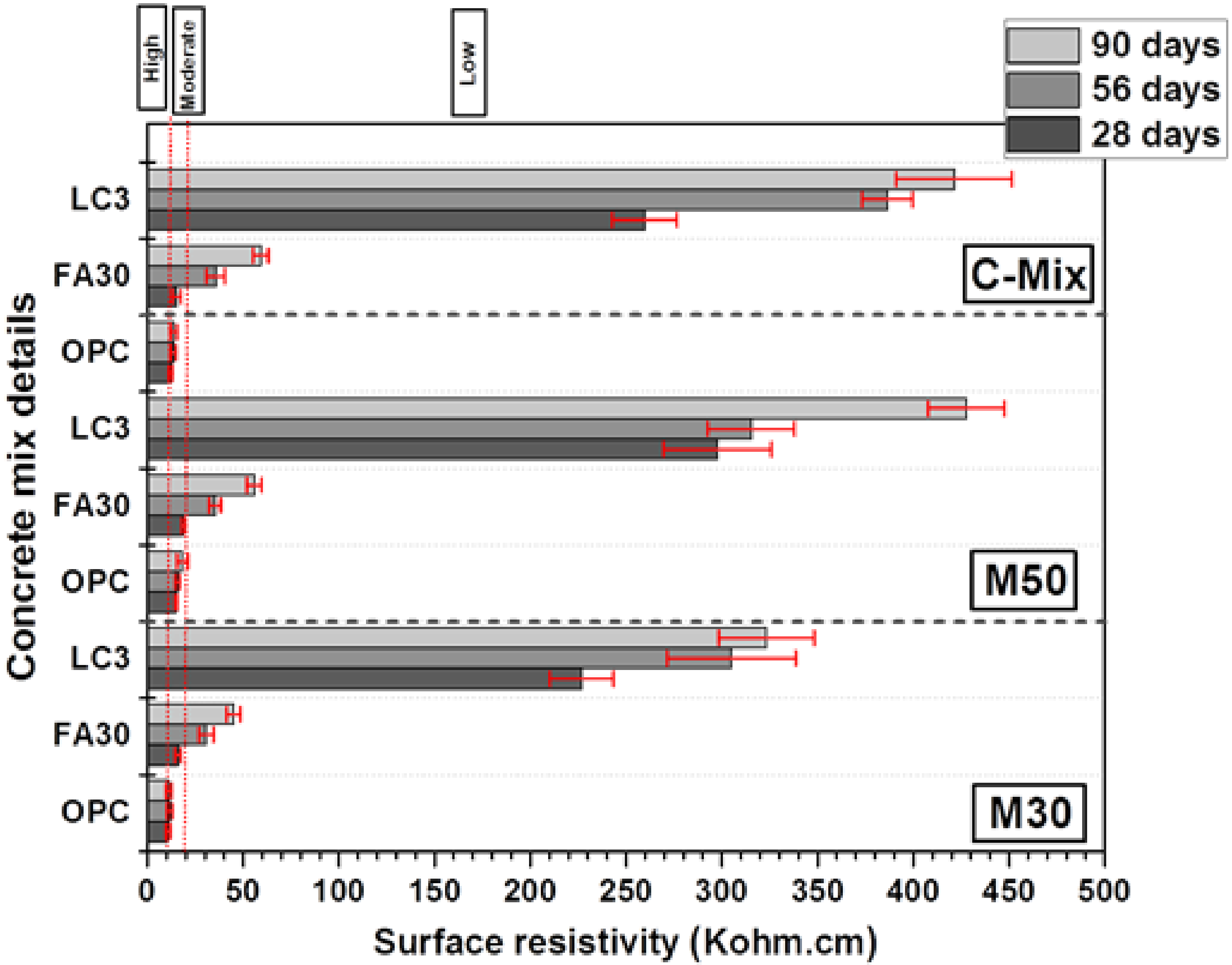
LC3-50(56)(2:1)1B

Strength development characteristics for LC^3 concretes matched with OPC concrete, and were better than fly ash based concrete in the early ages

Shrinkage of concrete



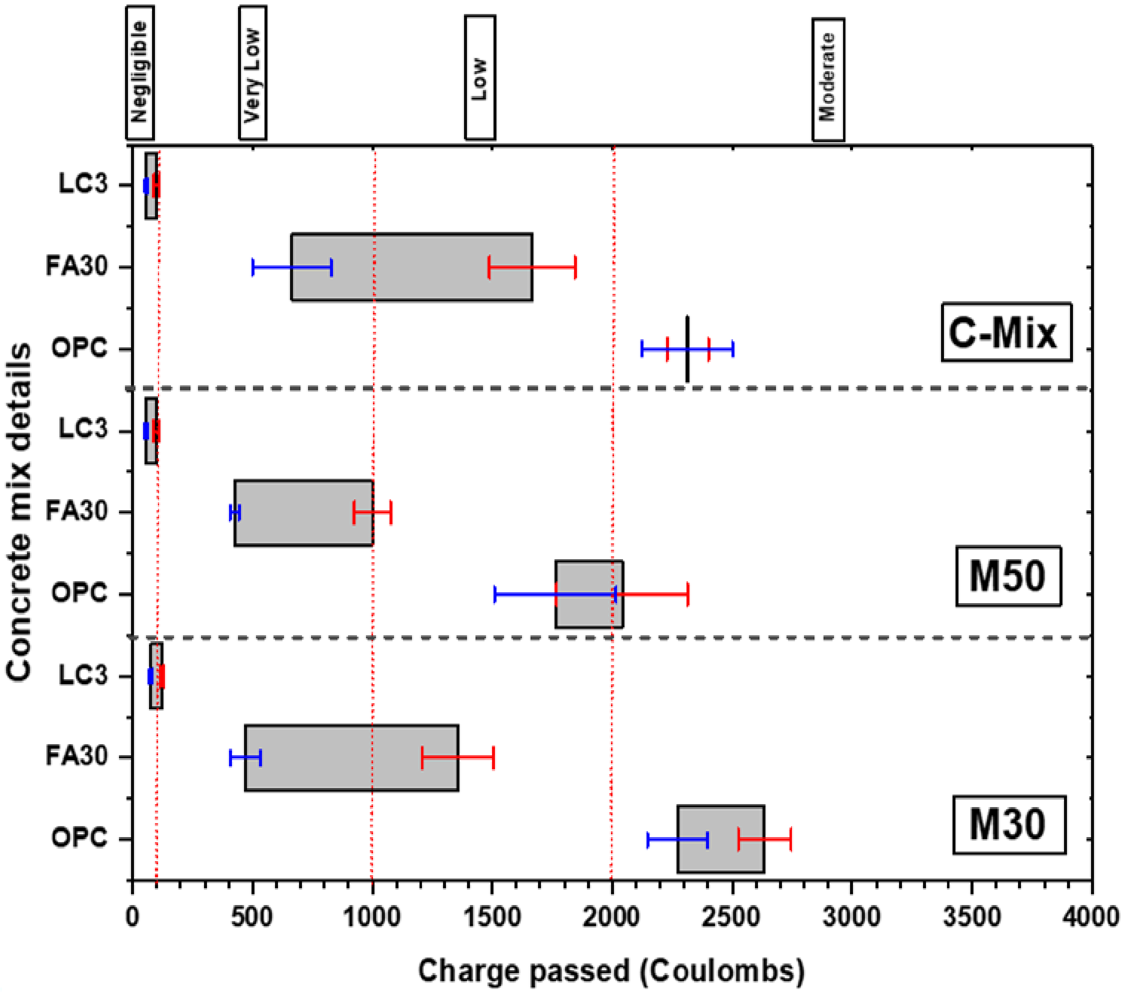
Surface resistivity



Resistivity of LC3 concretes was an order of magnitude higher than OPC (and also significantly higher than PPC) which suggests better resistance to corrosion propagation.

Chloride penetrability

by RCPT (ASTM C1202)

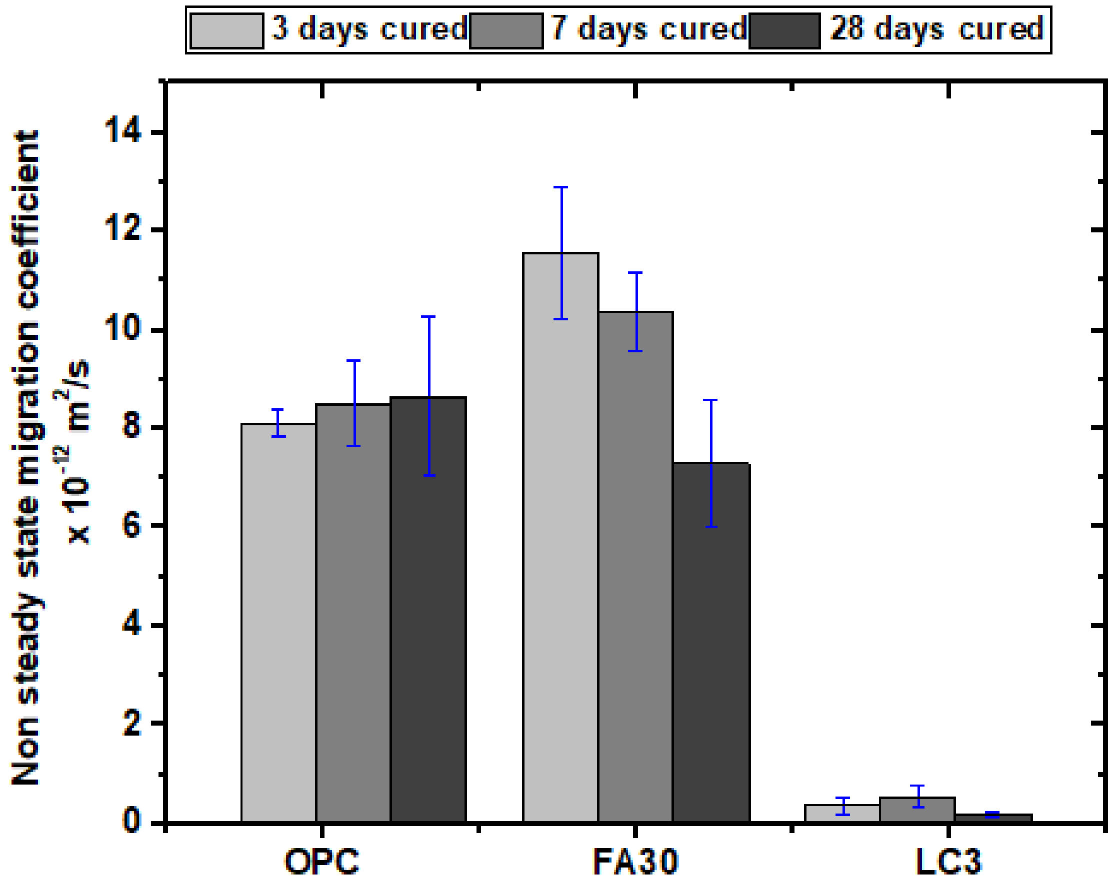


Red- 28 days Blue- 90 days

- There is a marked improvement of the chloride resistance at an early age irrespective of the different grades of concrete, unlike fly ash based PPC system which requires additional curing at higher water-binder ratios.

Chloride migration

by NT BUILD 492



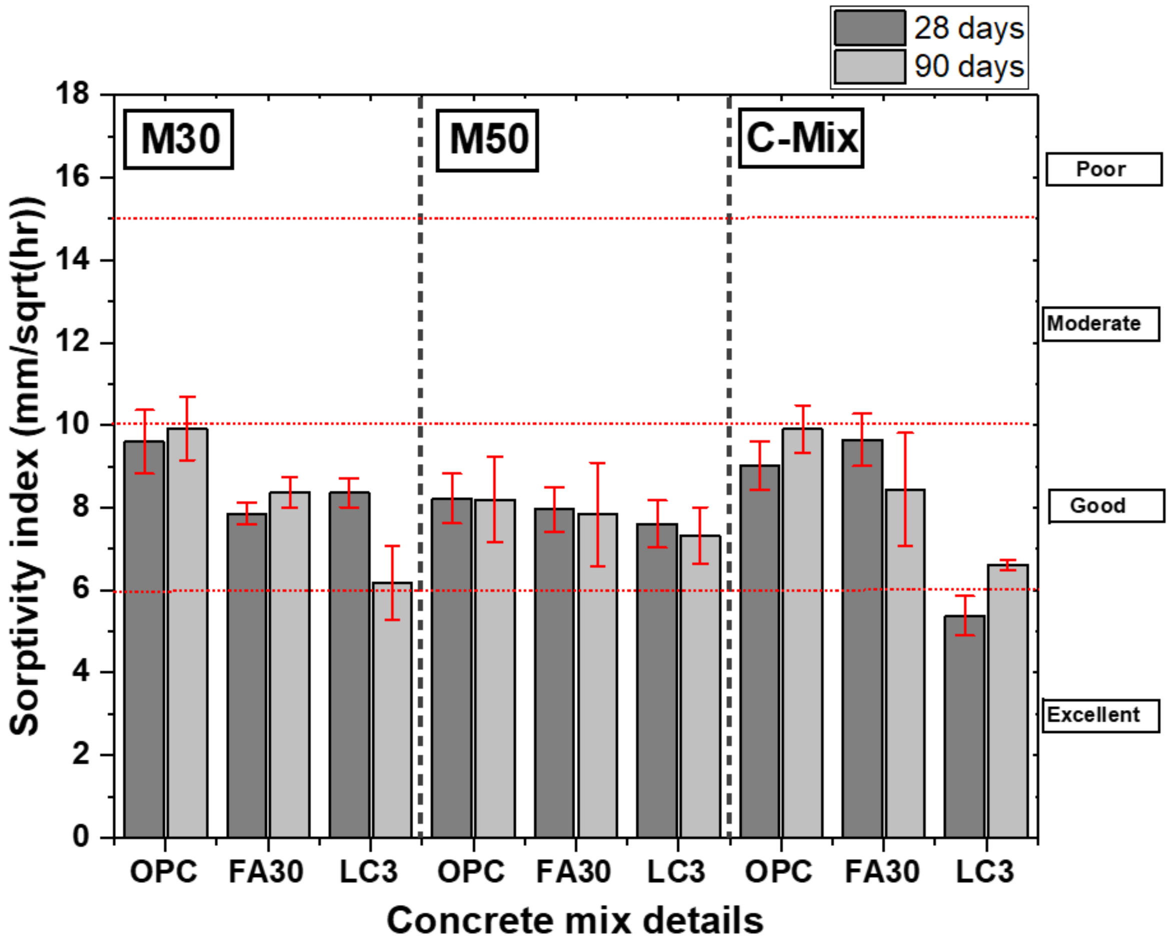
- Results shown for mixture with same binder content and w/b
- Tested at 28 days after different curing regime shows very low chloride migration coefficients – similar to high performance silica fume concrete! Also, lesser dependence on curing…

Influence of field curing

RC slabs subjected to field like curing using Hessian cloth for 14 days after which slab was exposed to environment

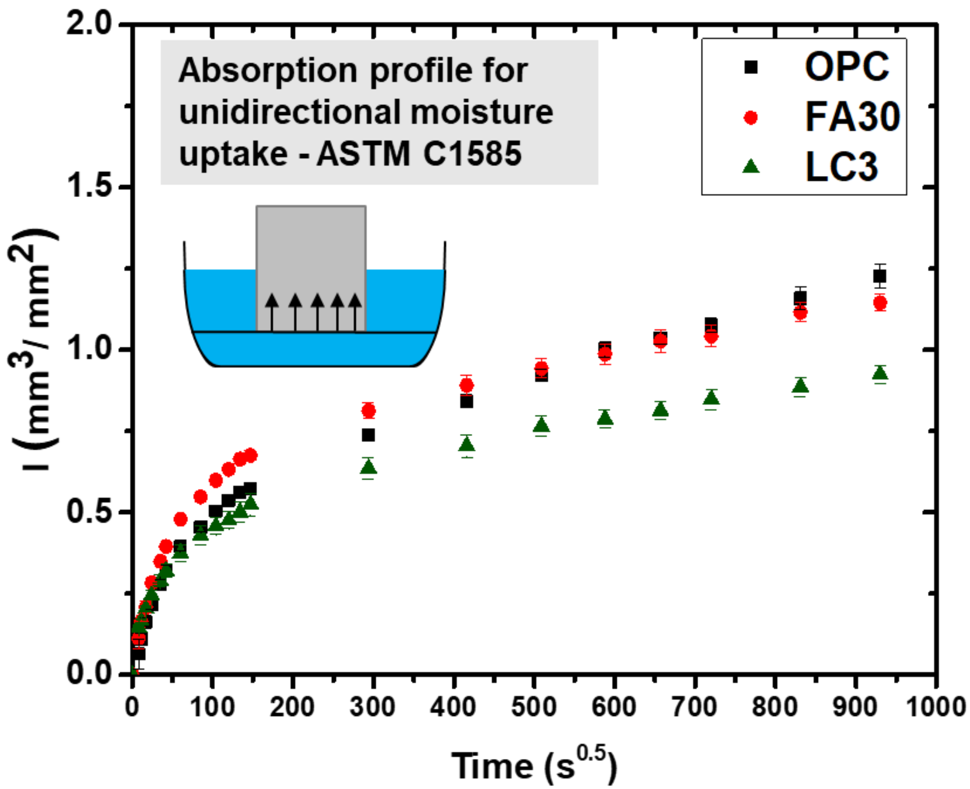
Binder system	Specimen details	Total charge passed (Coulombs)	Non-steady state diffusion coefficient (x 10^{-12} m^2/s)
LC3	Field specimens	160	1.77
	Lab specimens	120	1.98
PPC (Fly ash; 25 % replacement from Srinivasan et al. (2013))	Field Specimens	3050	12.50
	Lab specimens	1800	8.20

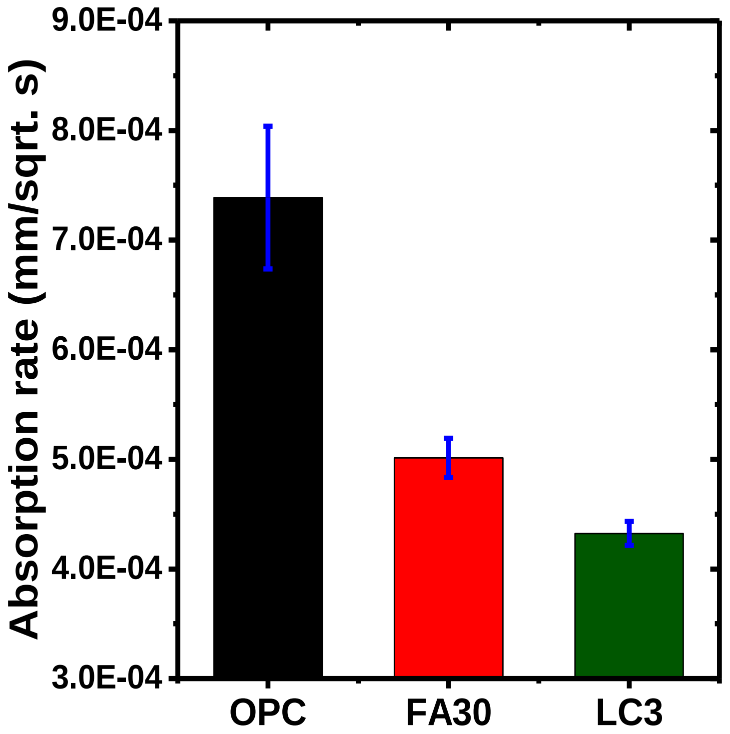
Water sorptivity



- Tortuous pore structure has reduced sorptivity in the LC3 system; FA30 system also has a relatively lower sorptivity compared to the OPC mix

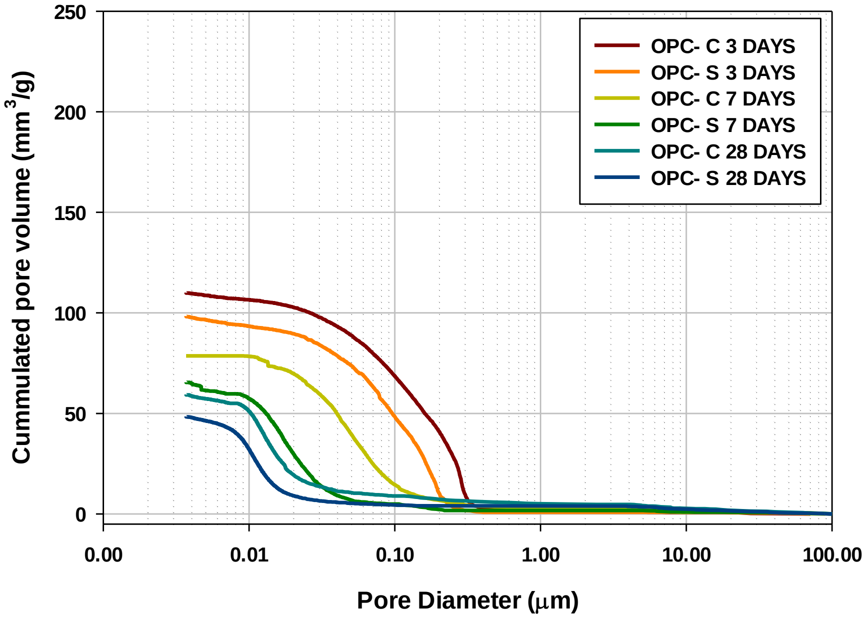
Water sorptivity – secondary absorption



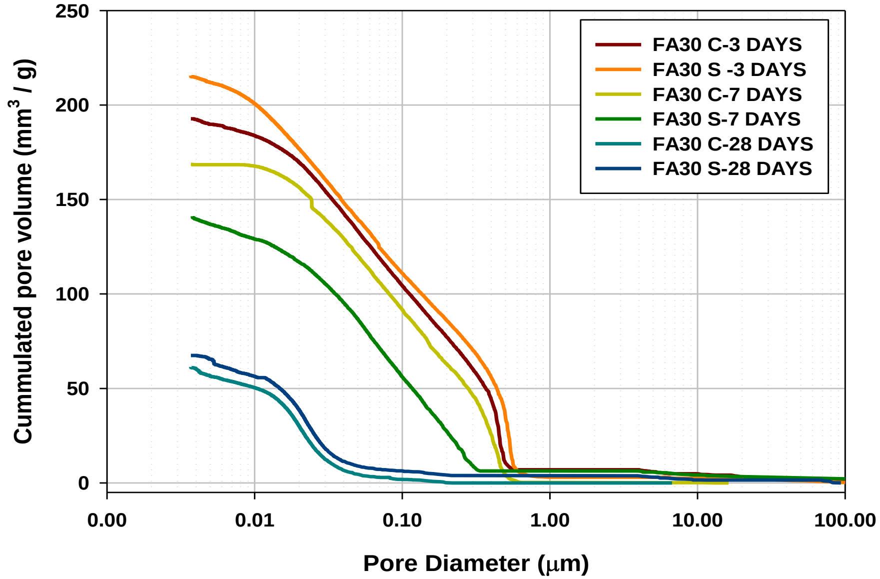


Secondary absorption rate as a measure of moisture ingress was found to be positively affected due to refined pore structure in LC3 binder

Pore structure evolution in LC^3

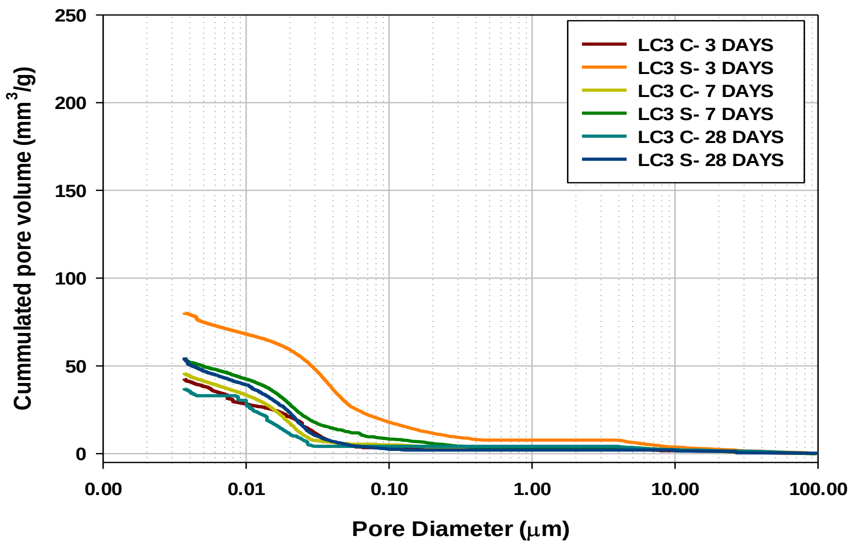


Cummulated Pore Volume Vs Pore diameter of OPC (w/c: 0.4)



Cummulated Pore Volume Vs Pore diameter of FA30 (w/c: 0.4)

- LC3 shows lowered threshold diameter even as early as at 3 days
- Refined pore structure major factor for better durability performance at early ages

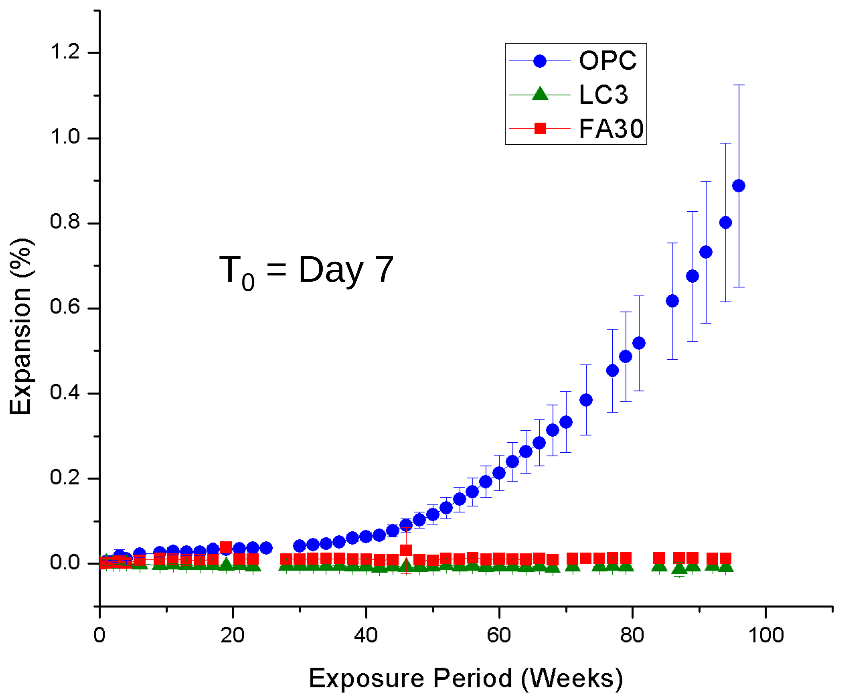


Cummulated Pore Volume Vs Pore diameter of LC3 (w/c: 0.4)

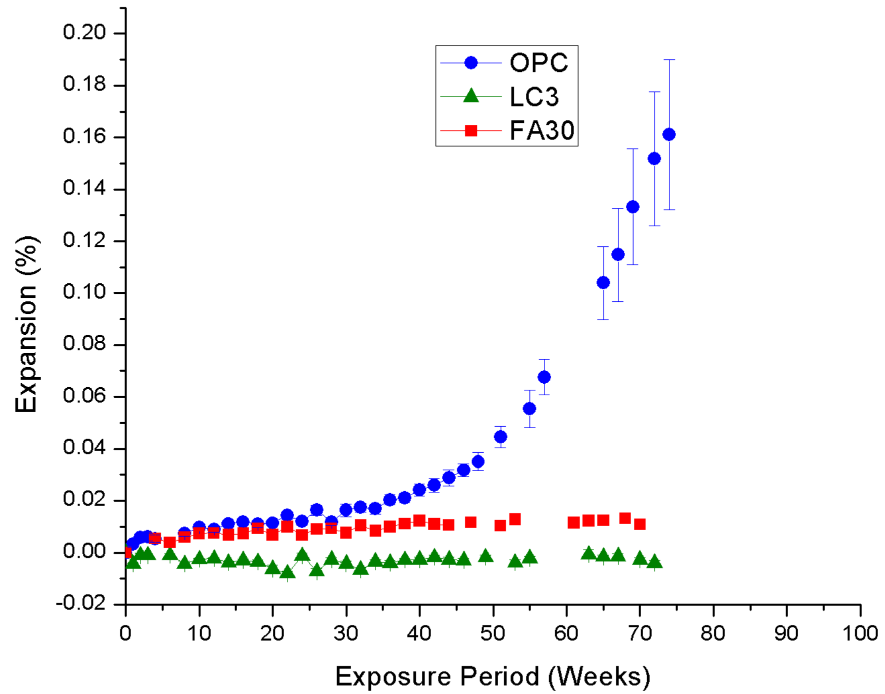
Sulphate Attack

Length change as per ASTM C1202

LC3-50(56)(2:1) IB



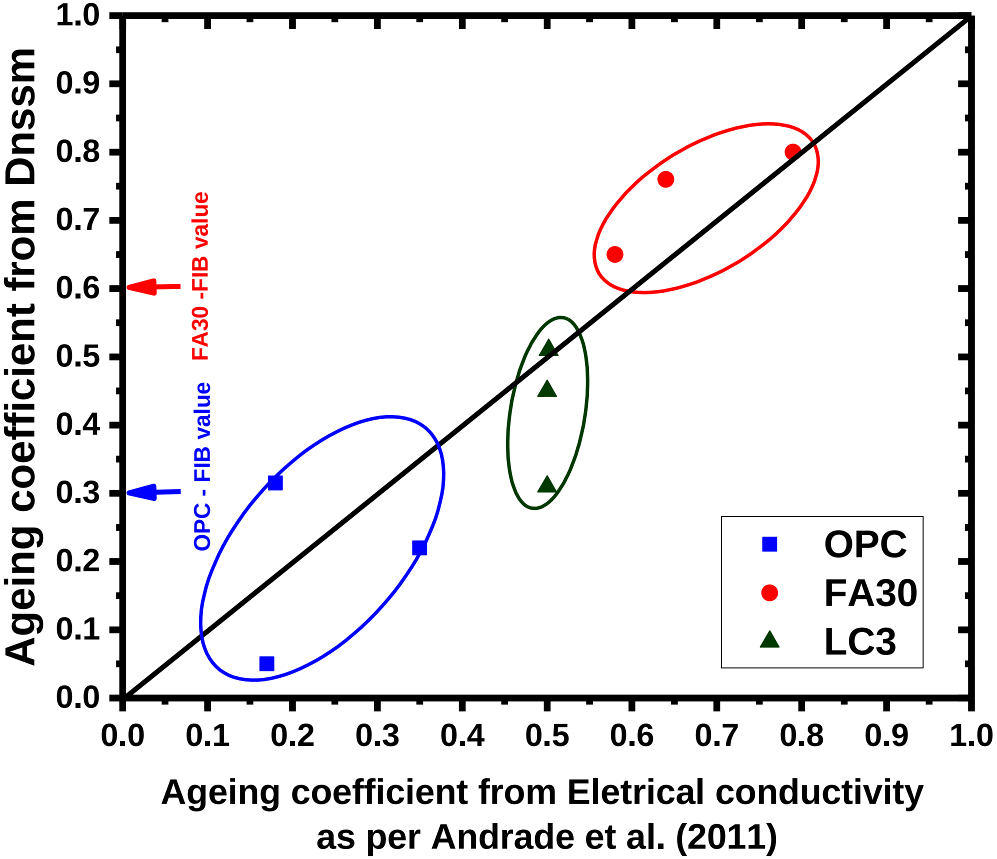
Sodium sulphate solution

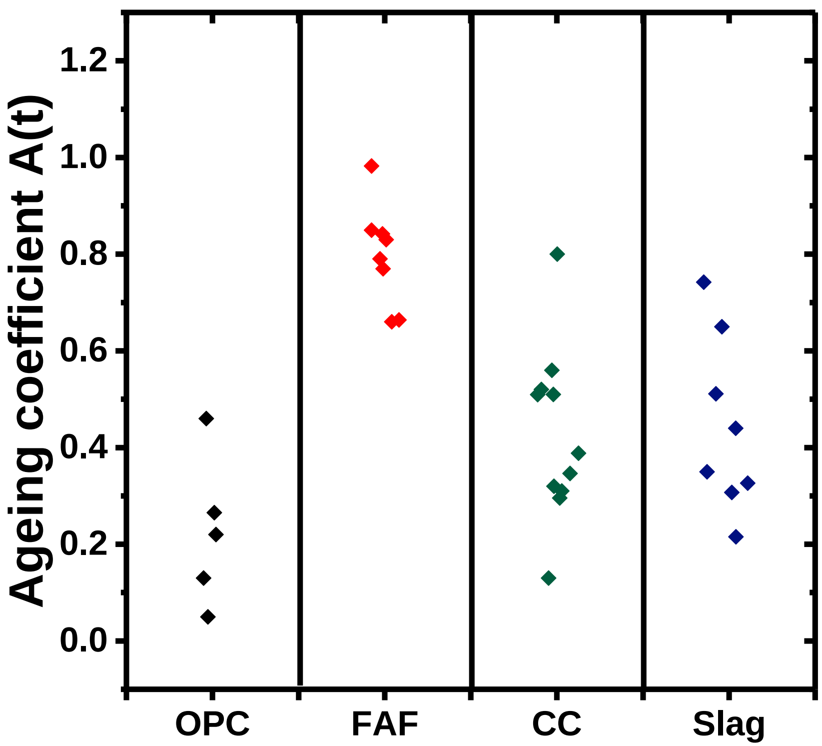


Magnesium sulphate solution

No expansion in LC3 and FA30 mortars even after more than 70 weeks of exposure; OPC mortars show very high expansion

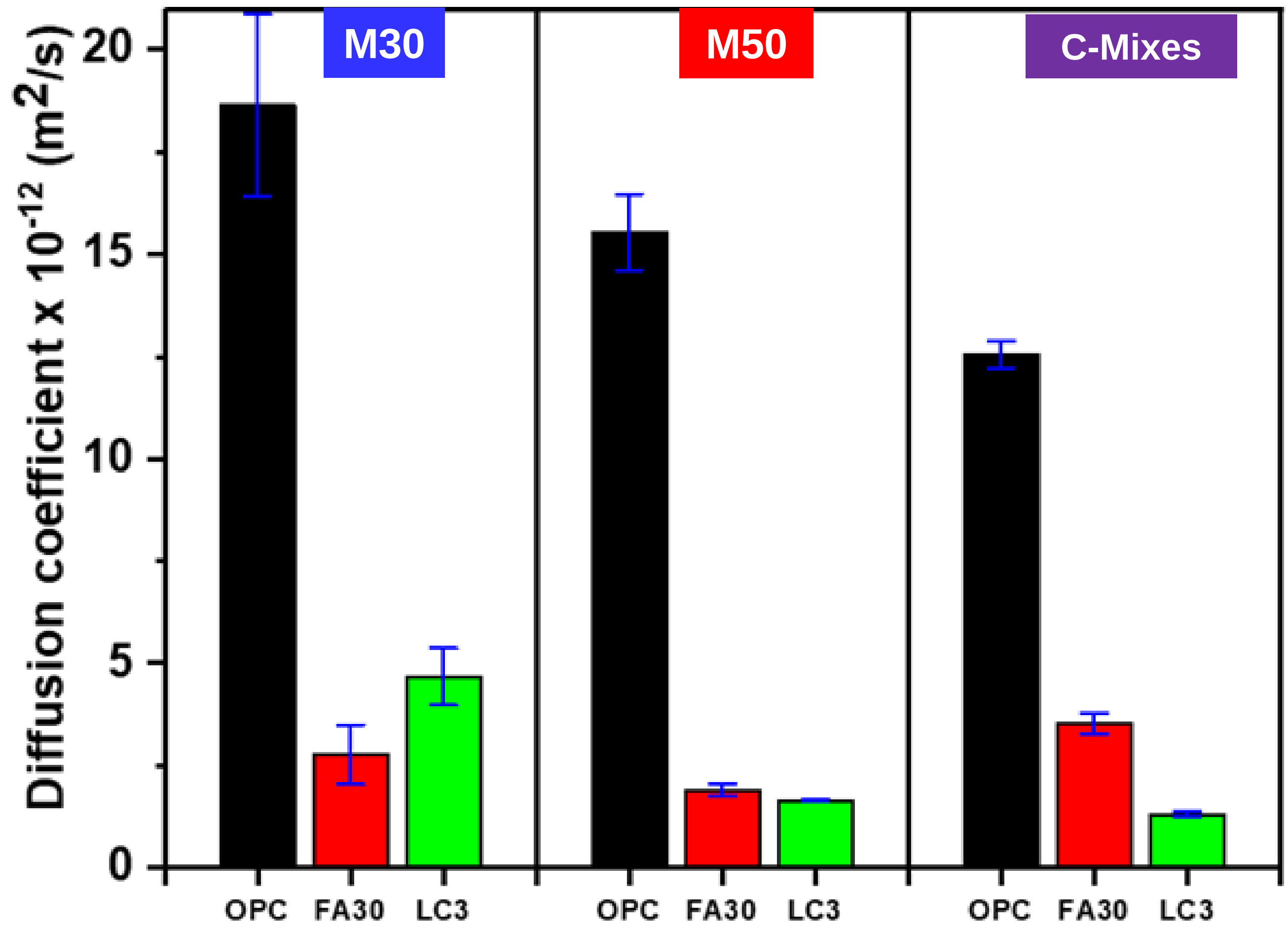
Progression of chloride transport characteristics with time



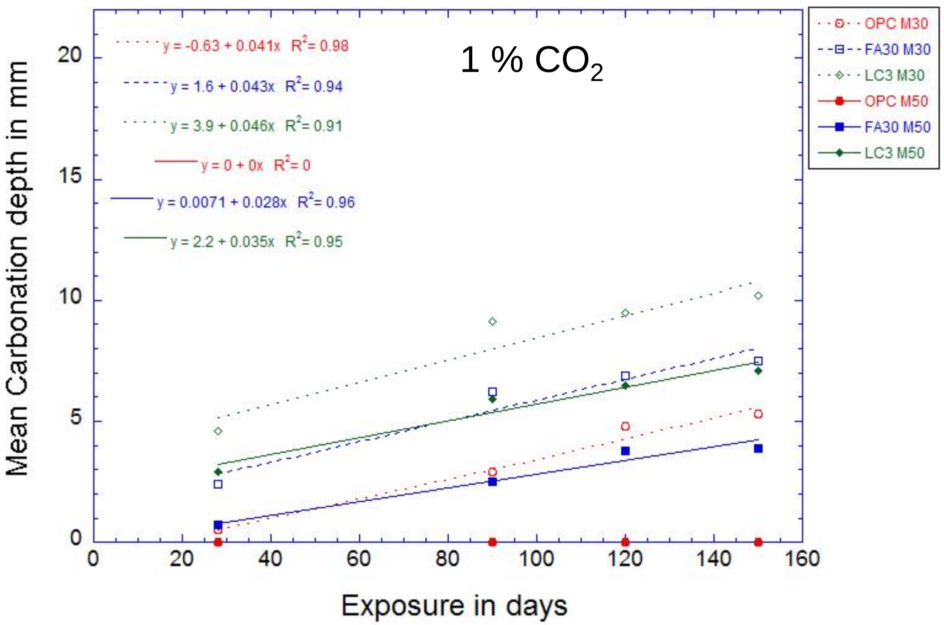


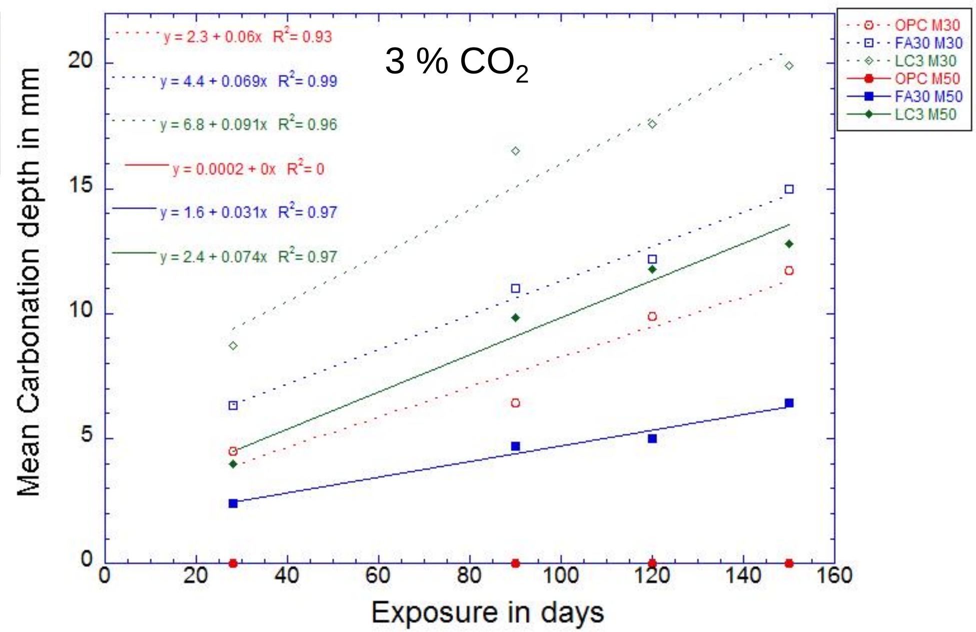
- Ageing coefficient is important for long term assessment of chloride induced corrosion performance – service life estimation for performance-based design approaches
- Calcined clay concrete has similar ageing to slag and lesser than fly ash concrete

Chloride profiles of the M30 and M50 grade of concrete (ASTM C1556) – Error Function solution – Diffusion coefficient



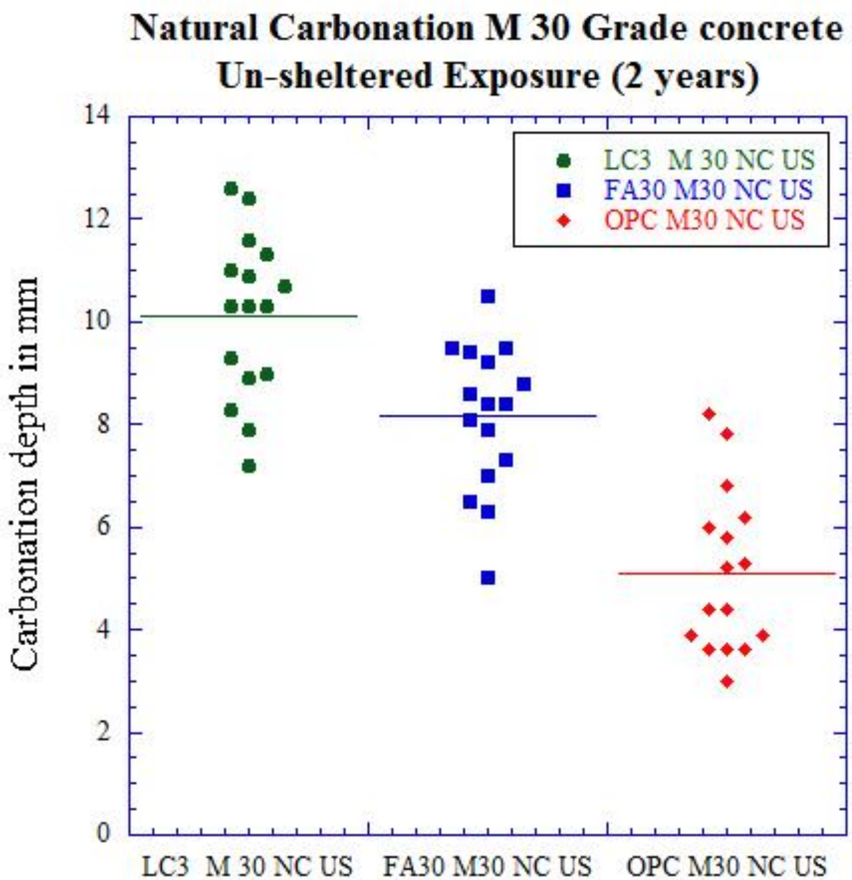
Evolution of carbonation depth in accelerated carbonation with respect to time in concrete grade M30 and M50

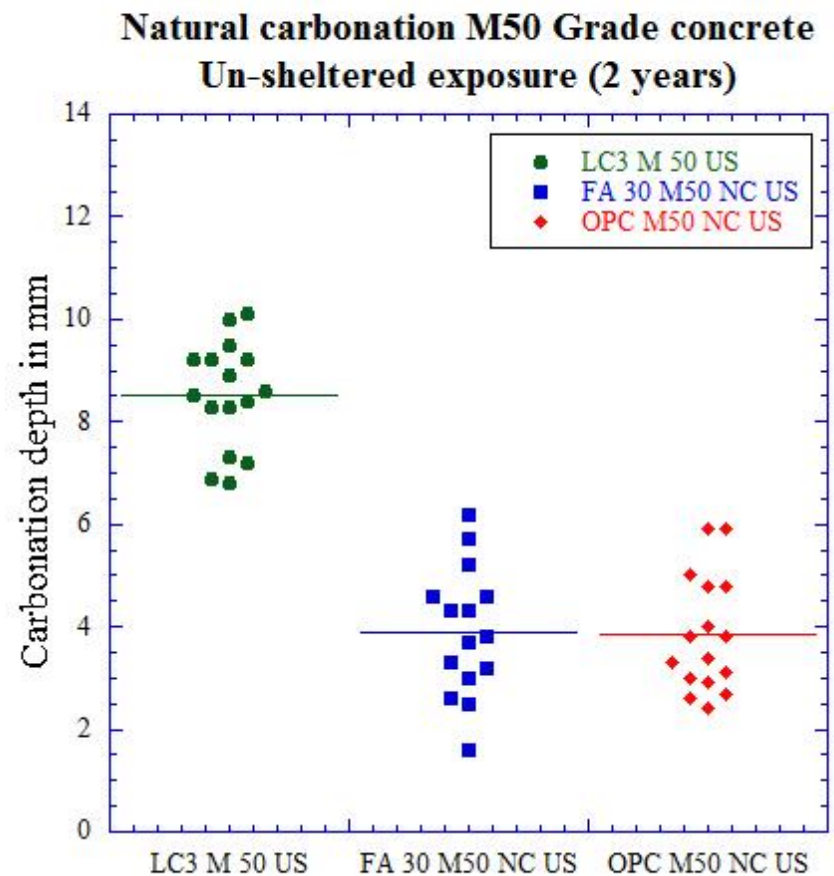




- Concrete elements cast with LC3 show lower carbonation resistance at similar strength grade in comparison with concretes made with OPC and FA30.
- Reason for lower carbonation resistance can be attributed to the lowered buffer capacity of calcium bearing hydrated compounds

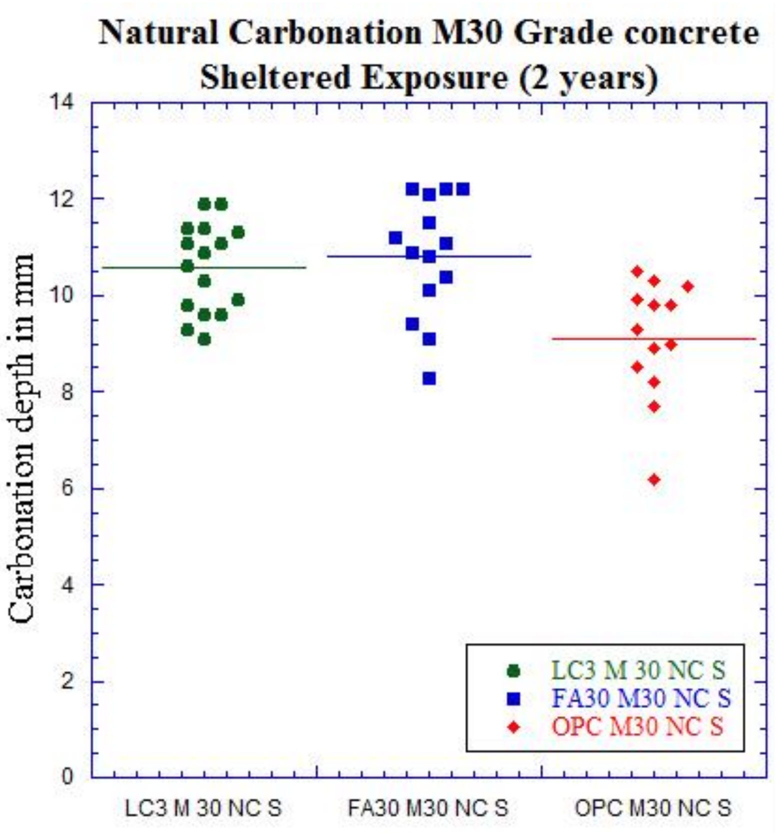
Natural Carbonation Results – Unsheltered exposure

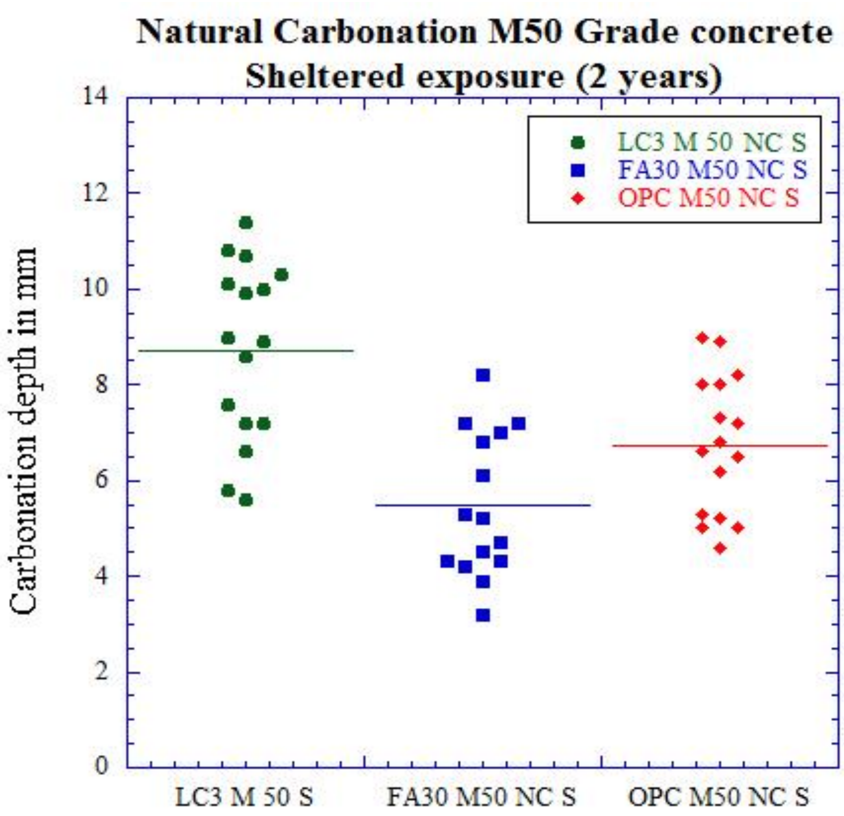




- After two years of exposure concrete specimens cast with LC3 showed higher carbonation than other cementitious systems at similar strength grades

Natural Carbonation Results – Sheltered exposure





- Carbonation depth in sheltered exposure is greater than unsheltered exposure due to relatively lesser micro climate variation

What does this mean for corrosion?

Corrosion Initiation

- Better chloride binding → lesser risk of chloride induced corrosion initiation
- Greater rate of carbonation → greater risk of corrosion initiation

Corrosion propagation

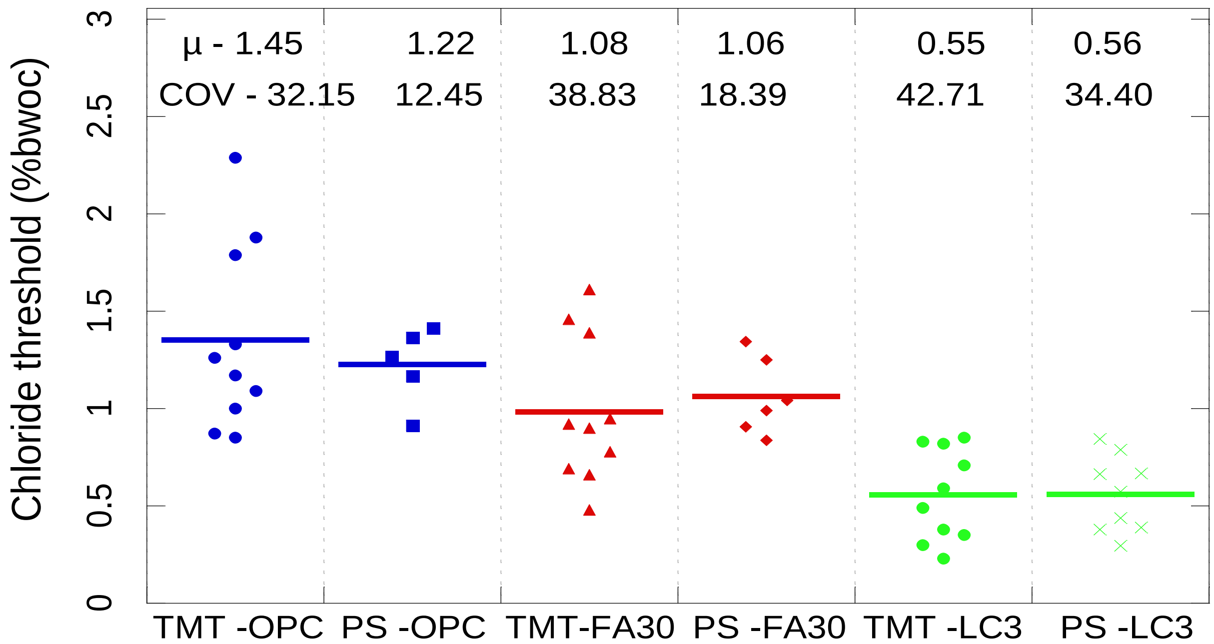
- Higher resistivity → reduced ionic conductivity, therefore reduced rate of corrosion propagation
- Better microstructure development → reduced moisture availability, therefore reduced rate of corrosion propagation

Let us now see how the performance can be translated to service life in a chloride environment...

But first, we also need to know the Chloride Threshold levels...

Chloride Threshold

»Measured by detecting the change in polarization resistance
»Test Variables
  »OPC ,FA30, LC3 Cementitious System; Mortar 1:2.75
  »QST Steel (8 mm dia)
  »Prestressing steel- king wire (5.2 mm dia)



Lollipop Test Specimen

LC3 system has less chloride threshold when compared to OPC and FA30 systems.

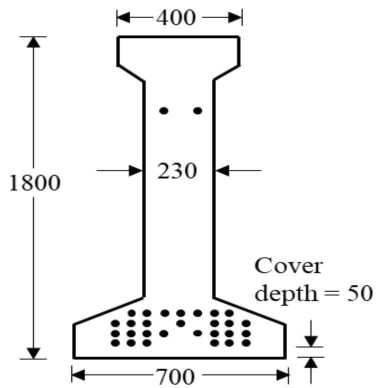
Estimation of Service Life

Test variables	Constants used
Clear cover, x	50 mm
Chloride diffusion coefficient, D_{Cl}	M50 grade concretes • OPC : 21.8 x 10^{-12} m^2/s • FA30: 7.8 x 10^{-12} m^2/s • LC3 : 6.6 x 10^{-12} m^2/s
Chloride threshold, Cl_{th}	• OPC : 0.44 %bwoc • FA30 : 0.32 %bwoc • LC3 : 0.17 %bwoc
Maximum chloride conc. at the concrete surface, $C_{s,\ max}$	$C_{s,\ max}$ = 3 % bwoc (0.6 % by wt. of concrete)
Surface chloride concentration build up rate (%)	0.04
Time for complete hydration (years)	25

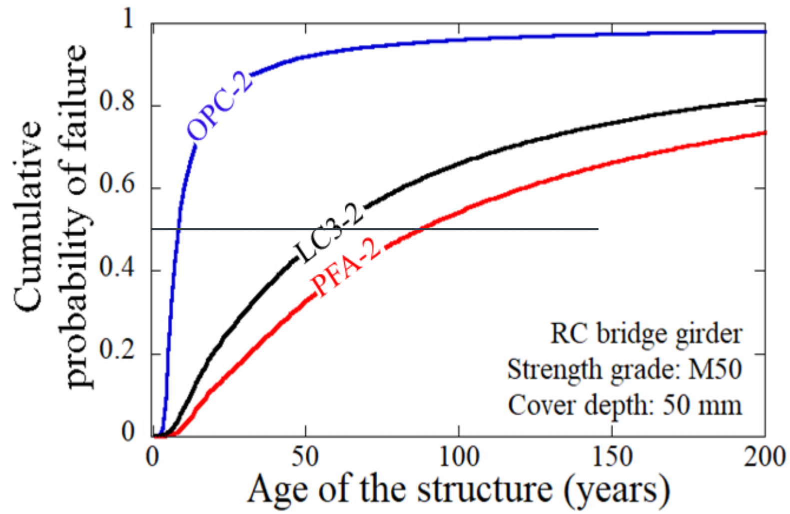
% bwoc → % by weight of cement

Courtesy: L&T Ramboll

Typical element of a bridge girder in India



(c) Cross section of bridge girder



(d) Cumulative distribution function (CDF) of time to corrosion initiation in bridge girder

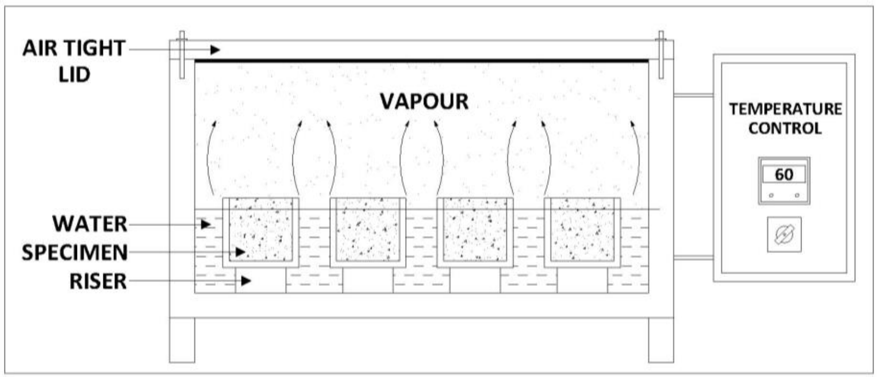
Service life ranking considering concretes of same strength grades

For M50 → FA30 > LC^3 >> OPC

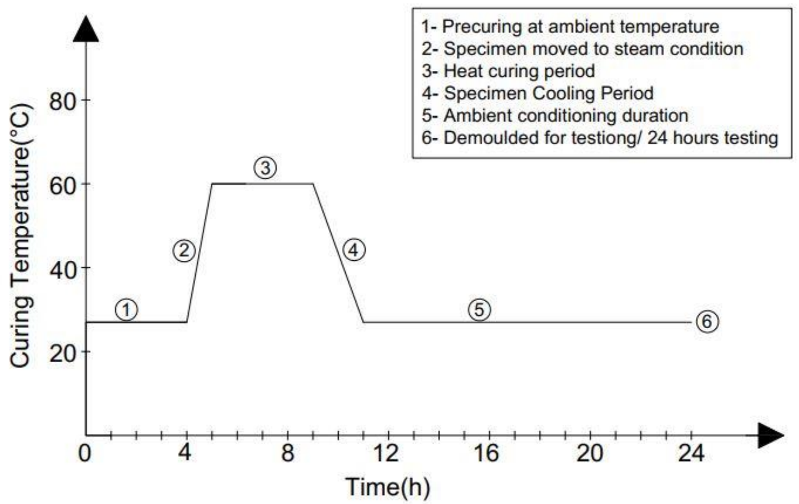
(Point to consider: FA30 mix has lower w/b)

Effects of short term heat curing

- Three binder proportions
  - OPC
  - FA30 (70% OPC + 30% Fly ash)
  - LC3 (55% OPC + 45% LC2)
- Two concrete mixture proportions
  - Binder content: 360 kg/m^3 and w/b – 0.45
  - Binder content: 400 kg/m^3 and w/b – 0.40
- Experiments carried out
  - Concrete strength evolution up to 90 days
  - Concrete Resistivity
  - Pore structure alteration due to steam curing using MIP (Paste: w/b – 0.4)
  - X ray diffraction for phase changes



SETUP FOR STEAM CURING OF SPECIMEN

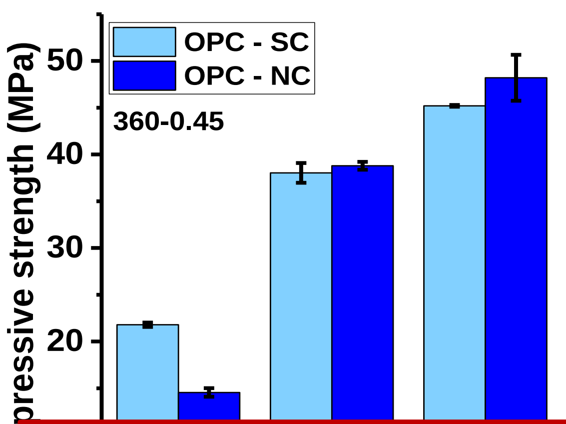


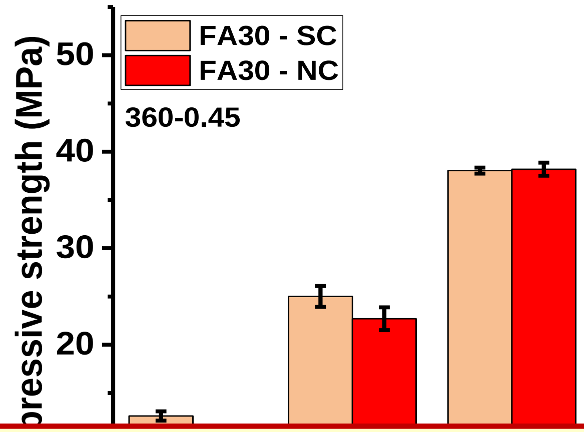
Steam Curing Regime

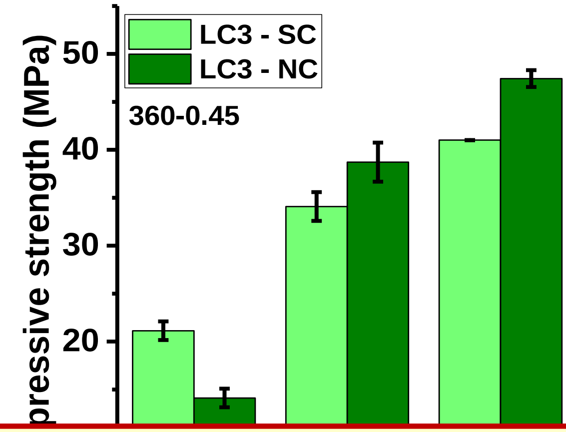
Limestone Calcined Clay Cement LC3

Compressive Strength
Normal cured Vs Steam cured

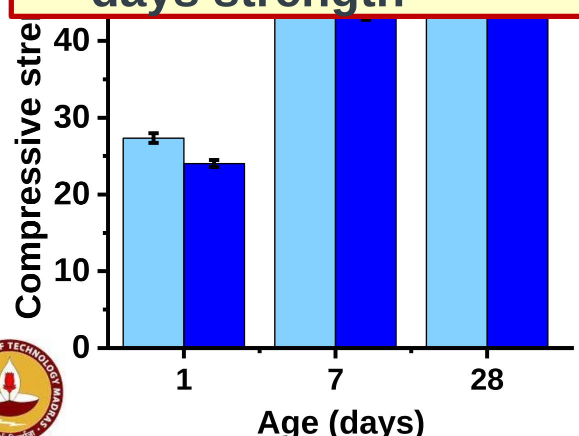
LOW CARBON LOW COST LOW CAPITAL

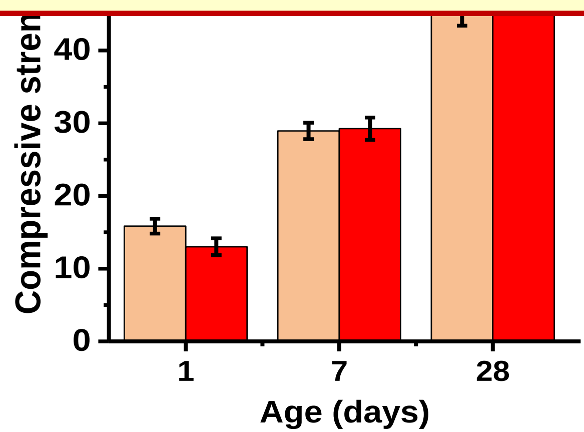


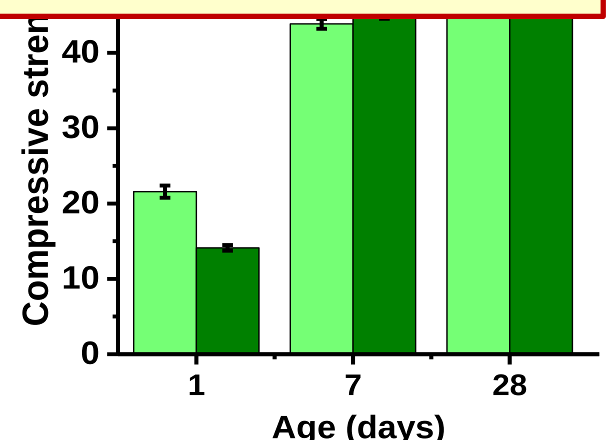




- **Early increase in strength noticed with OPC and LC3**
- **Difference in 28 days strength due to short term heat curing is less than 10-15% for OPC and LC3 compared to moist cured concrete**
- **Fly ash concrete negligible rise in early strength and limited change 28 days strength**



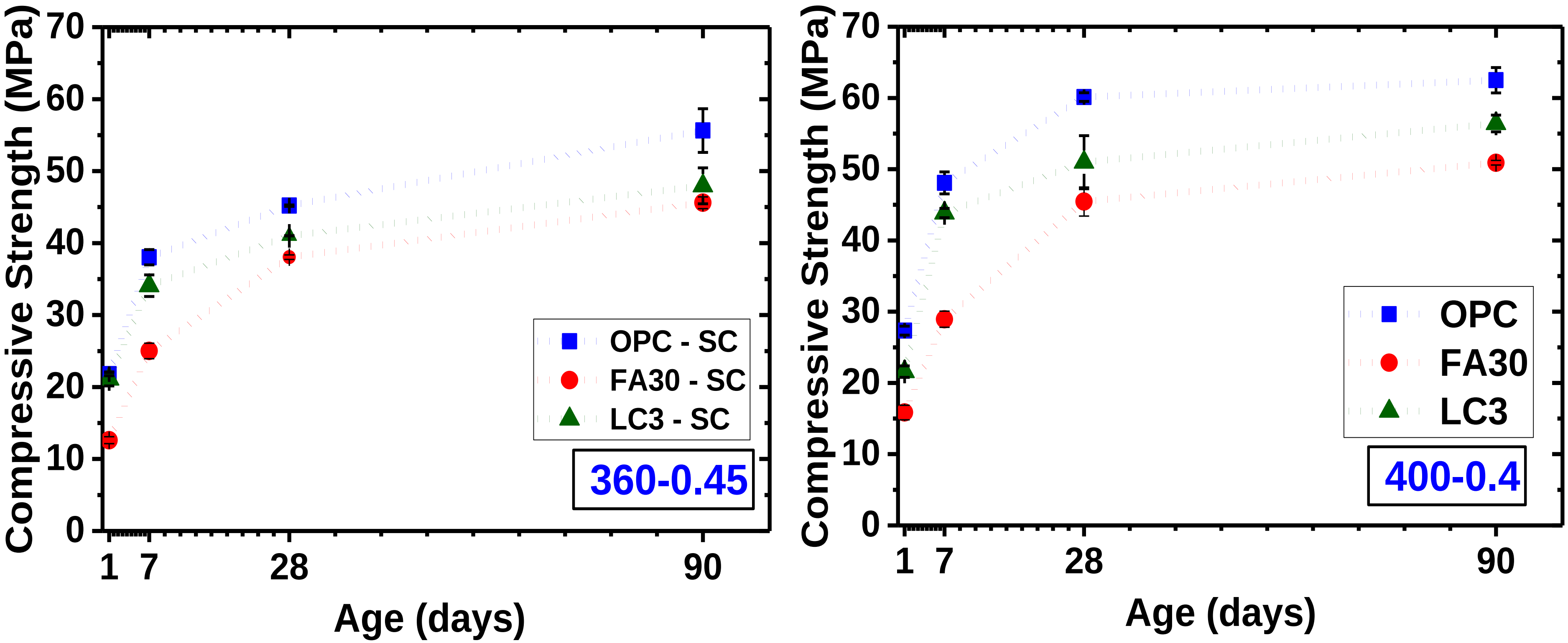




Limestone Calcined Clay Cement LC3

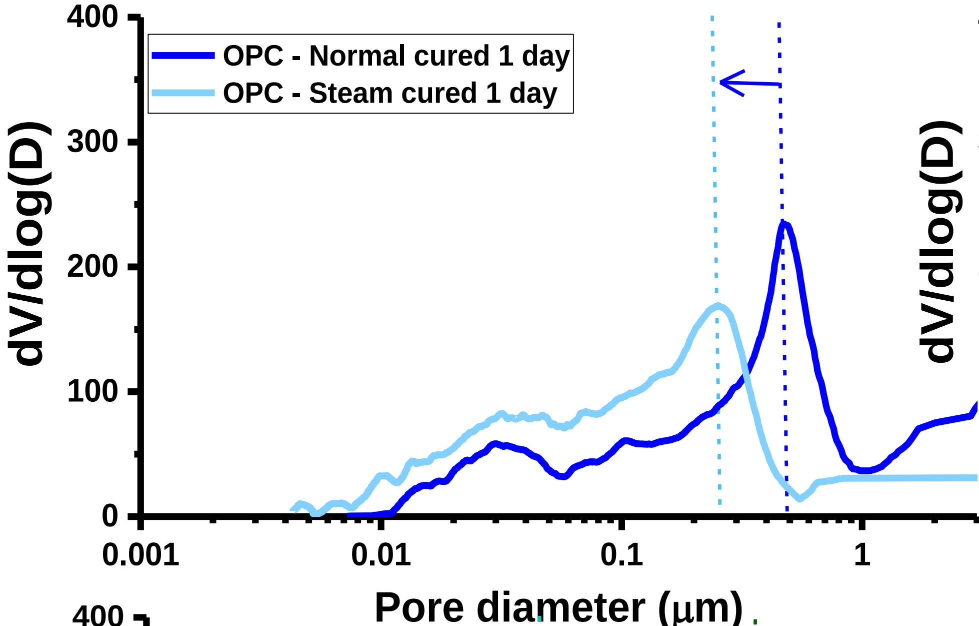
LOW CARBON LOW COST LOW CAPITAL

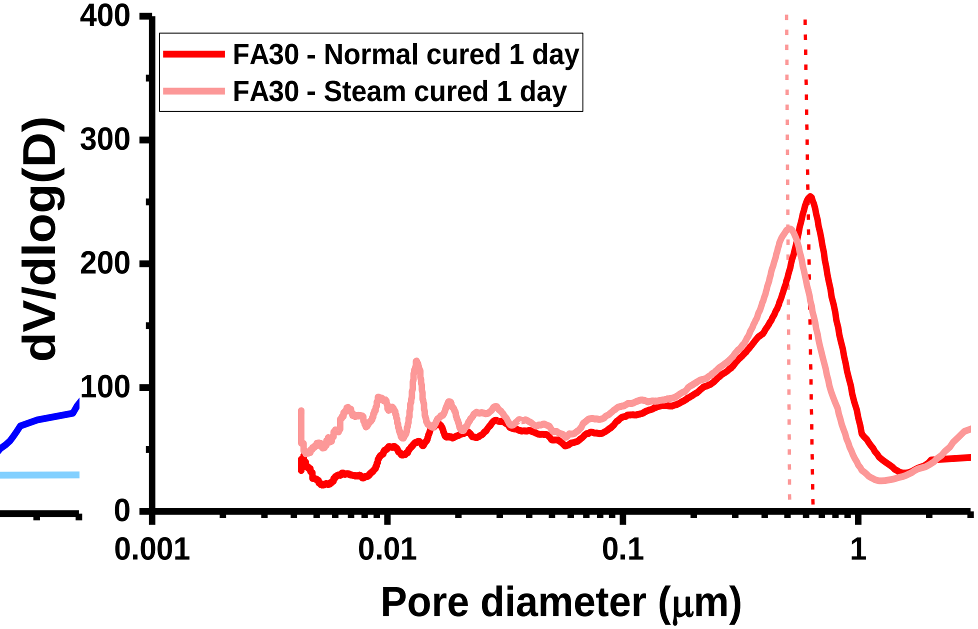
Strength evolution subjected to short-term heat cured concrete

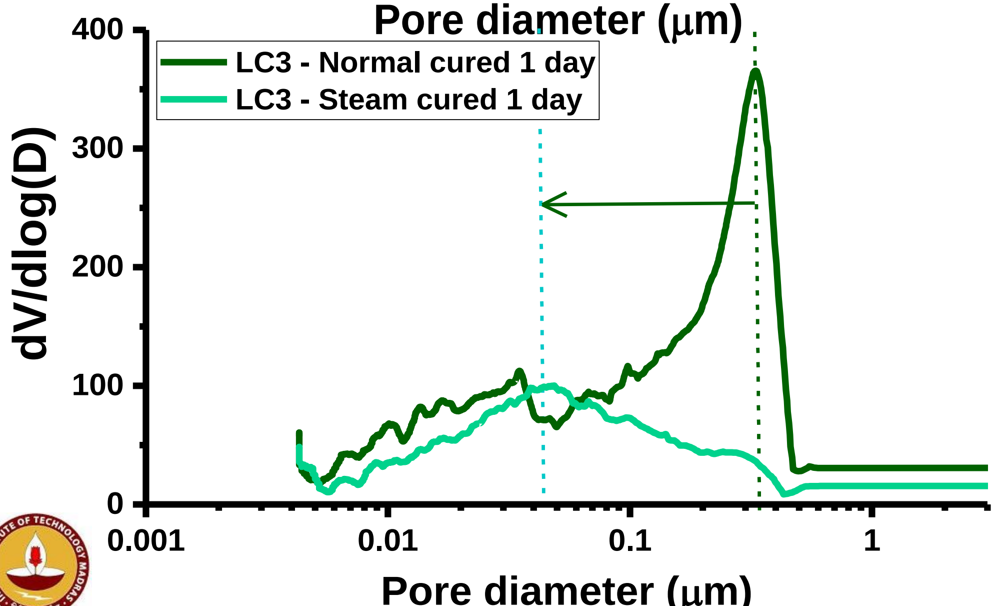


- No stagnation of strength was found in OPC, FA30 and LC3 concrete
- Strength up to 7 days were similar for OPC and LC3 – the difference were higher at later ages

1-d pore structure alteration due to heat curing

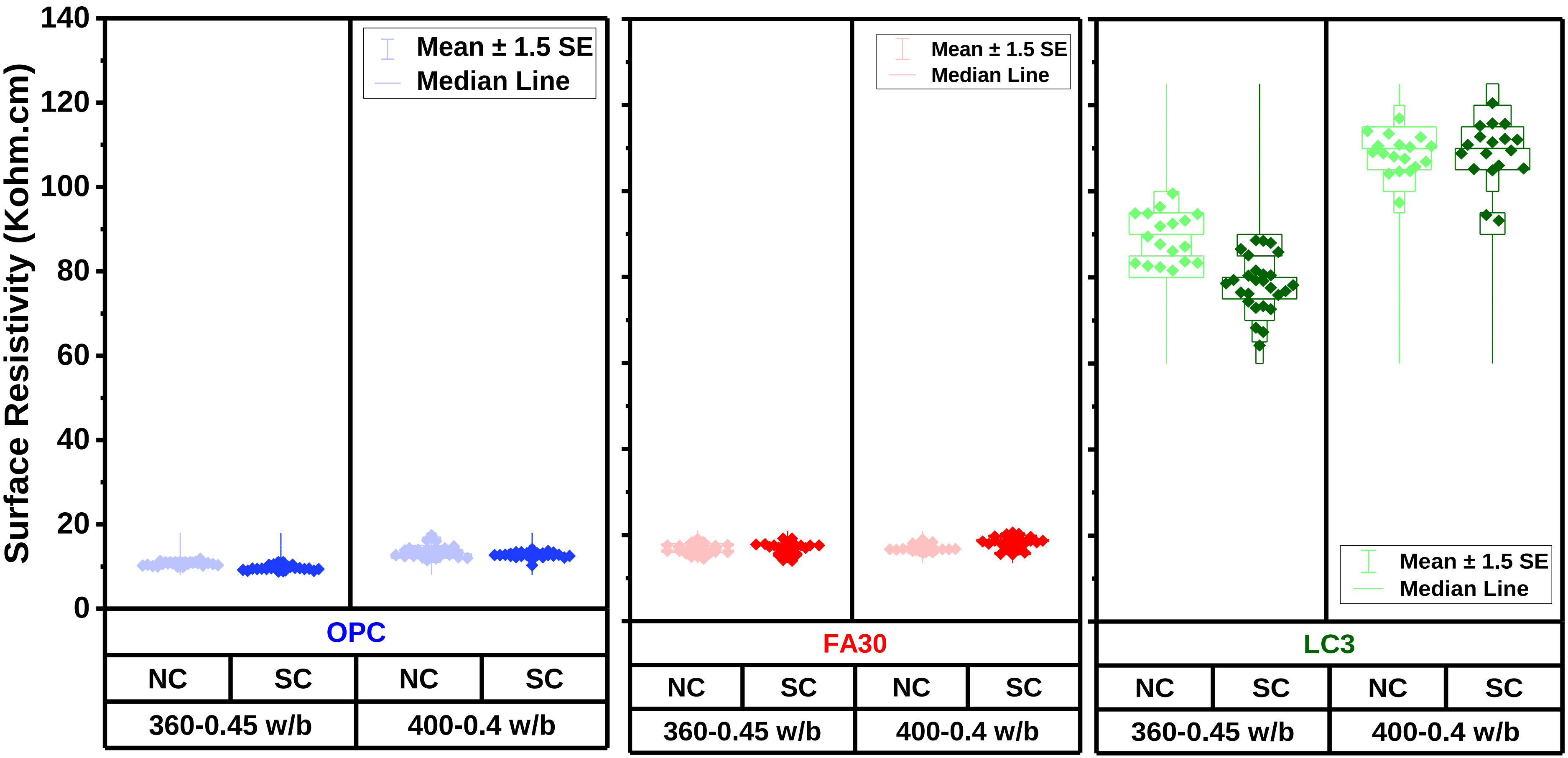






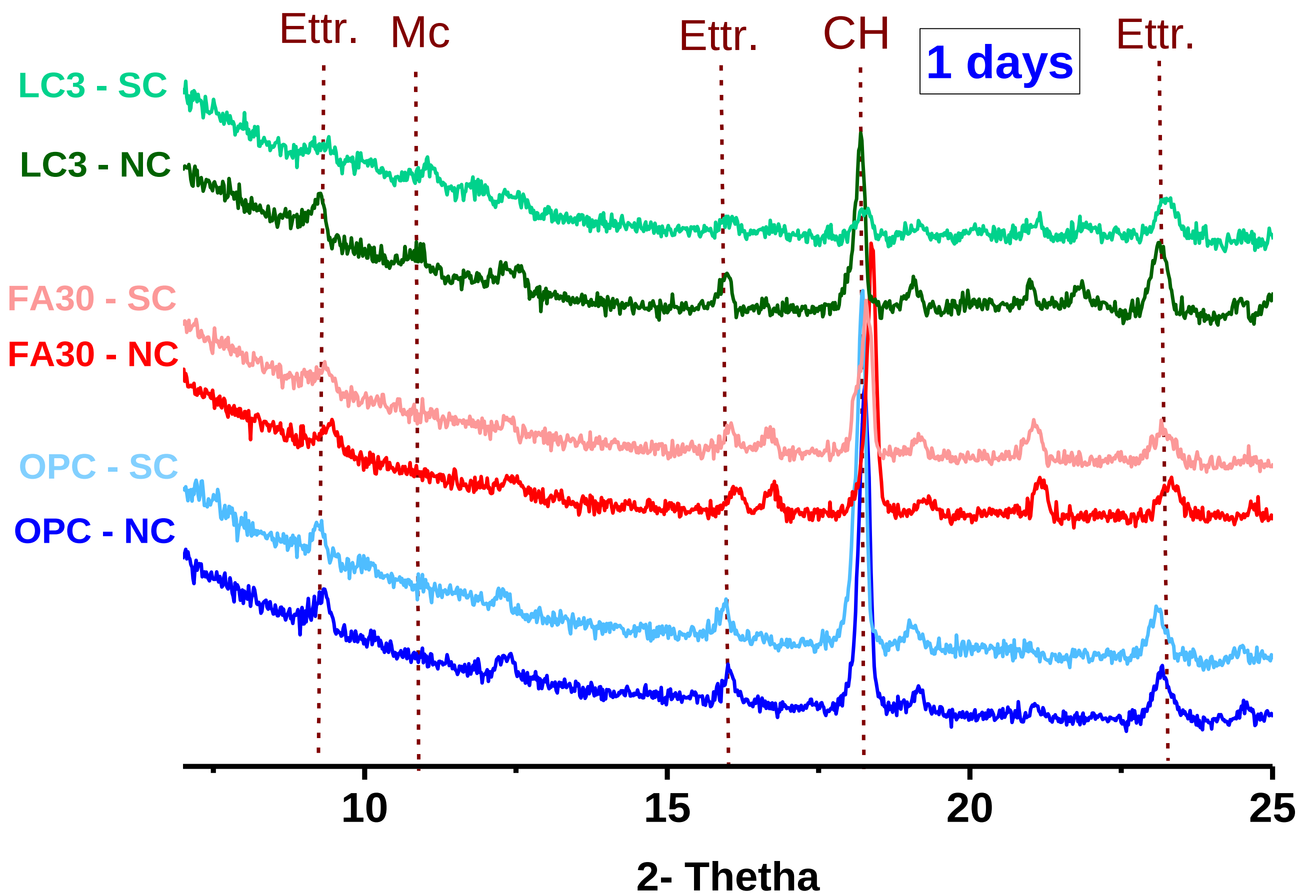
- Short term heat curing reduces the pore sizes dominantly in LC3
- Fly ash have limited effect on the pore structure due to steam curing
  - Explains minimal change in strength development

Change in durability indices due to heat curing



- 28 days resistivity value reduced marginally for all binders subjected to heat curing – the difference was rather insignificant

Phase change due to short term heat curing



- Ettringite and Mc phase are diminishing due to heat curing
- Acceleration of calcined clay reaction is confirmed by CH consumption

Summary of results on short term heat curing

- Initial strength gain after steam curing followed the order
  - OPC>LC3>FA30
- Strength development up to 90 days was not affected due to short-term heat curing
  - Strength development rate were different for three binders.
    - OPC>LC3>>FA30
  - Ultimate strength reduction after short-term heat cured for OPC, FA30 and LC3 were less than 15%
  - No stagnation of strength development due to reduced clinker content or enhanced reactivity of calcined clay was notice in concrete
- Pore structure was studied after short-term heat curing.
  - LC3>>OPC>FA30
  - Resistivity as durability indices showed minor reduction. However, the reduction was rather limited

Conclusions

- Limestone-calcined clay ternary systems show good strength development at early ages, and result in superior pore structure characteristics.
- Resistance to chloride penetration is much better with LC^3 concretes as opposed to OPC - at long term, fly ash concretes and LC3 concretes are similar
- Carbonation of LC^3 is higher than fly ash concrete, but this is mainly because of higher replacement levels of the cement – high resistivity and low moisture penetration may be beneficial in restricting corrosion propagation
- Possible to use LC^3 in heat cured concrete without any negative effects

Thank you

Support from SDC is gratefully acknowledged