Performance of LC³ 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

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Mix I.D.</th>
<th>w/b</th>
<th>Cement</th>
<th>Fly ash</th>
<th>Water content</th>
<th>Fine aggregate</th>
<th>Coarse aggregate</th>
<th>SP dosage (% wt. of cement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OPC-M30</td>
<td>0.50</td>
<td>310</td>
<td>0</td>
<td>155</td>
<td>695</td>
<td>496</td>
<td>744</td>
</tr>
<tr>
<td>2</td>
<td>FA30-M30</td>
<td>0.45</td>
<td>217</td>
<td>93</td>
<td>140</td>
<td>723</td>
<td>491</td>
<td>737</td>
</tr>
<tr>
<td>3</td>
<td>LC³-M30</td>
<td>0.50</td>
<td>310</td>
<td>0</td>
<td>155</td>
<td>708</td>
<td>491</td>
<td>736</td>
</tr>
<tr>
<td>4</td>
<td>OPC-M50</td>
<td>0.40</td>
<td>360</td>
<td>0</td>
<td>144</td>
<td>703</td>
<td>477</td>
<td>716</td>
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<tr>
<td>5</td>
<td>FA30-M50</td>
<td>0.35</td>
<td>266</td>
<td>114</td>
<td>133</td>
<td>699</td>
<td>475</td>
<td>713</td>
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<tr>
<td>6</td>
<td>LC³-M50</td>
<td>0.40</td>
<td>340</td>
<td>0</td>
<td>136</td>
<td>704</td>
<td>488</td>
<td>732</td>
</tr>
<tr>
<td>7</td>
<td>OPC-C</td>
<td>0.45</td>
<td>360</td>
<td>0</td>
<td>162</td>
<td>721</td>
<td>463</td>
<td>694</td>
</tr>
<tr>
<td>8</td>
<td>FA30-C</td>
<td>0.45</td>
<td>252</td>
<td>108</td>
<td>162</td>
<td>721</td>
<td>463</td>
<td>694</td>
</tr>
<tr>
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<td>0.45</td>
<td>360</td>
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<td>162</td>
<td>721</td>
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<td>694</td>
</tr>
</tbody>
</table>

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
Strength development characteristics for LC³ concretes matched with OPC concrete, and were better than fly ash based concrete in the early ages.
Shrinkage of concrete

- OPC-C
- FA30-C
- LC³-C
- C-Mix

Total shrinkage

Increase in autogenous shrinkage

Exposure time \((t-t_0)\), days

Shrinkage (microstrain)
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.
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

<table>
<thead>
<tr>
<th>Binder system</th>
<th>Specimen details</th>
<th>Total charge passed (Coulombs)</th>
<th>Non-steady state diffusion coefficient ($ \times 10^{-12} \text{m}^2/\text{s}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC3</td>
<td>Field specimens</td>
<td>160</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>Lab specimens</td>
<td>120</td>
<td>1.98</td>
</tr>
<tr>
<td>PPC (Fly ash; 25 % replacement from Srinivasan et al. (2013))</td>
<td>Field Specimens</td>
<td>3050</td>
<td>12.50</td>
</tr>
<tr>
<td></td>
<td>Lab specimens</td>
<td>1800</td>
<td>8.20</td>
</tr>
</tbody>
</table>

RC slabs subjected to field like curing using Hessian cloth for 14 days after which slab was exposed to environment.
Tortuous pore structure has reduced sorptivity in the LC3 system; FA30 system also has a relatively lower sorptivity compared to the OPC mix.
Secondary absorption rate as a measure of moisture ingress was found to be positively affected due to refined pore structure in LC3 binder.
LC3 shows lowered threshold diameter even as early as at 3 days
• Refined pore structure major factor for better durability performance at early ages
Sulphate Attack

Length change as per ASTM C1202

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

Sodium sulphate solution

Magnesium sulphate solution

$T_0 = \text{Day 7}$
• 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
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...
» 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)

<table>
<thead>
<tr>
<th>System</th>
<th>Chloride Threshold (%bwoc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMT-OPC</td>
<td>µ - 1.45, COV - 32.15</td>
</tr>
<tr>
<td>PS-OPC</td>
<td>1.22, 12.45</td>
</tr>
<tr>
<td>TMT-FA30</td>
<td>1.08, 38.83</td>
</tr>
<tr>
<td>PS-FA30</td>
<td>1.06, 18.39</td>
</tr>
<tr>
<td>TMT-LC3</td>
<td>0.55, 42.71</td>
</tr>
<tr>
<td>PS-LC3</td>
<td>0.56, 34.40</td>
</tr>
</tbody>
</table>

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

% bwoc $\rightarrow$ % by weight of cement
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
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
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
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.
• 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 LC³ concretes as opposed to OPC - at long term, fly ash concretes and LC3 concretes are similar. Carbonation of LC³ 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 LC³ in heat cured concrete without any negative effects.
Thank you

Support from SDC is gratefully acknowledged