Development of Lightweight Self-compacting Concrete (LWSCC)

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Production Requirements of SCC

- Higher powder content (cement + filler) and/or viscosity-modifying admixture
- Better quality control on grading of aggregates
- More accurate control of total moisture
- Higher cost for powder and new type of superplasticiser
Impact on Conventional Precasting Operation

- New types moulds – lighter and without form vibrators
- Smaller footprints – using vertical casting for elements
- Greater flexibility in finishes – both faces of element
- Higher flexibility in design – complex bar arrangement
Lightweight Concrete

- Lower dead weight
- Easier transportation
- Larger precast elements for same tower crane capacity
- Better insulation
Concern of the use of Lightweight Concrete

- Mechanical properties
- Durability (permeability, carbonation)
- Cost
Worldwide coal ash production:
~ 500 Mt of ash produced per annum and this is expected to increase
Hong Kong - Coal Fired Power Plant
Pulverized Fuel Ash (PFA)

- Steam output to turbines: both high- and low-pressure steam
- Coal from blending plant
- Coal pulverisers
- Furnace bottom ash
- Furnace
- Fly ash
- Electrostatic precipitators
- To storage silos or conditioners
- Exhaust stack
Castle Peak pulverised fuel ash

PFA collected in precipitators → Ash Classification Plant (ACP).

Classified PFA (CPFA) has a fineness value where no more than 12.5% is retained on the 45 micron sieve

Conforms to British Standard 3892 Part 1-1982 for the production of structural concrete

Used as a cement substitute in concrete and building blocks

Reject Ash - oversized material from ACP is not used for structural concrete

Pumped through pipelines to a lagoon, 5.5 kilometres north of the station
Classification of PFA

PFA

45μm

Rejected and kept no use

Used for building and S/S materials

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Pulverized Fuel Ash (PFA)

- By-product from burn-out of pulverized coal in power stations
- Fine alumino-silicate powder
- Glassy spheres, together with crystalline matter and unburned carbon
Particles of Fly Ashes

Spherical shapes of f-FA particles

Irregular shapes of r-FA particles
Furnace Bottom Ash (FBA)
Objectives of Research

- To use r-FA as a replacement of viscosity agent in normal and lightweight SCC mixtures
- To investigate the influences of r-FA on the fresh and hardened properties of NORMAL WEIGHT SCC mixtures
- To investigate the influences of r-FA and FBA on the fresh and hardened properties of LIGHTWEIGHT SCC mixtures
## Chemical Composition of Fly Ashes

<table>
<thead>
<tr>
<th>Type</th>
<th>SiO$_2$</th>
<th>Fe$_2$O$_3$</th>
<th>Al$_2$O$_3$</th>
<th>TiO$_2$</th>
<th>CaO</th>
<th>LOI</th>
<th>Fineness (m$^2$/kg)</th>
<th>Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r-FA</td>
<td>47.2</td>
<td>8.4</td>
<td>24.5</td>
<td>1.0</td>
<td>8.3</td>
<td>8.1</td>
<td>119.0</td>
<td>2.19</td>
</tr>
<tr>
<td>f-FA</td>
<td>47.6</td>
<td>7.4</td>
<td>27.4</td>
<td>1.2</td>
<td>8.1</td>
<td>0.9</td>
<td>399.6</td>
<td>2.28</td>
</tr>
</tbody>
</table>
Size Distribution of r-FA

![Graph showing the size distribution of f-FA and r-FA.](image)
Benefits of Using r-FA

- Pozzolanic properties of fly ashes
- Replacement of limestone fillers and mineral powders
- Replacement of viscosity agent
- By-product in electricity generation
- Additional benefits of economy
Requirements of SCC Mixtures

- Initial slump flow = 650 mm
- Slump flow value of 650 mm to be maintained over a period of 2 hours
- A minimum blocking ratio of 0.75 measured using the L-box apparatus
- Segregation ratio between 5 % and 15 %
Normal Weight SCC
# Mix Proportions for Normal Weight SCC Mixtures

<table>
<thead>
<tr>
<th>Mix</th>
<th>OPC (kg/m³)</th>
<th>f-FA (kg/m³)</th>
<th>r-FA (kg/m³)</th>
<th>Aggregate (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>w/b</th>
<th>w/p</th>
<th>SP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>375</td>
<td>125</td>
<td>0</td>
<td>400</td>
<td>860</td>
<td>200</td>
<td>0.4</td>
<td>0.4</td>
<td>1.7</td>
</tr>
<tr>
<td>2</td>
<td>375</td>
<td>125</td>
<td>100</td>
<td>400</td>
<td>740</td>
<td>200</td>
<td>0.4</td>
<td>0.34</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>375</td>
<td>125</td>
<td>150</td>
<td>400</td>
<td>680</td>
<td>200</td>
<td>0.4</td>
<td>0.32</td>
<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>375</td>
<td>125</td>
<td>200</td>
<td>400</td>
<td>620</td>
<td>200</td>
<td>0.4</td>
<td>0.30</td>
<td>1.7</td>
</tr>
<tr>
<td>5</td>
<td>375</td>
<td>125</td>
<td>250</td>
<td>400</td>
<td>560</td>
<td>200</td>
<td>0.4</td>
<td>0.28</td>
<td>2.1</td>
</tr>
</tbody>
</table>

* Viscosity agent of 1.1 % by weight of binder (OPC+f-FA) was added
Fresh Properties

- Slump flow
- L-box
- Wet density
- Segregation
SCC with Lightweight Aggregates
Hardened properties

- Compressive strength (1, 4, 7, 28 and 90 days)
- Tensile strength (28 days)
- E-value (28 days)
- Wet and oven dry densities
Durability

- Chloride permeability
- Drying shrinkage
## Fresh properties of Normal Weight SCC with r-FA

<table>
<thead>
<tr>
<th>Mix</th>
<th>Slump flow (mm)</th>
<th>L-box</th>
<th>Wet density (kg/m³)</th>
<th>Air content (%)</th>
<th>Segregation degree (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Immediately after mixing</td>
<td>2 hours after mixing</td>
<td>Final time (s)</td>
<td>Blocking ratio</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Time (s)</td>
<td>Flow (mm)</td>
<td>Time (s)</td>
<td>Flow (mm)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>36</td>
<td>690</td>
<td>40</td>
<td>688</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>41</td>
<td>760</td>
<td>40</td>
<td>705</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
<td>755</td>
<td>41</td>
<td>710</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>49</td>
<td>835</td>
<td>28</td>
<td>765</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>718</td>
<td>40</td>
<td>685</td>
<td>40</td>
</tr>
</tbody>
</table>

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Fresh Properties of Normal Weight SCC with r-FA

- Slump flow values of the SCC mixtures were acceptable (>650 mm).
- The addition of r-FA could cause a reduction in the blocking ratio.
- Segregation ratio was satisfactory
- r-FA could be used as a replacement of viscosity agent
Tests for Hardened Properties

- Compressive strength
- Elastic modulus
- Chloride ion penetration (ASTM C1202)
Compressive Strength

![Chart showing compressive strength over time for different mixes.](chart)
Compressive Strength

- Control mixture had the lowest strength at all ages.
- Mix #5, which contained the highest amount of r-FA, had the highest strength at all ages.
- The strength increased as the r-FA content increased.
- The increased strength was due to the pozzolanic effect of r-FA and the improved packing within the concrete matrix.
Elastic Modulus

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Chloride Ion Penetration

Increasing resistance

Mix #

Total charge passed (Coulombs)

1 2 3 4 5
Relationship between Strength and Elastic Modulus

\[ y = 0.2093x + 18.327 \]
\[ R^2 = 0.9082 \]
Hardened Properties

- Elastic modulus increased with an increase in the r-FA content.
- A 15% increase in elastic modulus was observed when r-FA content increased from 0 to 250 kg/m$^3$.
- Resistance to chloride ion penetration improved as the r-FA content increased.
- A good correlation existed between strength and elastic modulus.
Lightweight SCC
Lightweight Aggregates
## Aggregate Properties

<table>
<thead>
<tr>
<th></th>
<th>Lightweight Aggregate (Leca)</th>
<th>Sand</th>
<th>FBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water absorption (%)</td>
<td>25.0</td>
<td>0.9</td>
<td>17.0</td>
</tr>
<tr>
<td>SSD density (kg/m³)</td>
<td>1355</td>
<td>2620</td>
<td>2190</td>
</tr>
<tr>
<td>Drying shrinkage (%)</td>
<td>&lt;0.05%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TFV (kN)</td>
<td>106</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fineness modulus (FM)</td>
<td>5.70</td>
<td>2.28</td>
<td>2.22</td>
</tr>
</tbody>
</table>
# Mix Proportions

<table>
<thead>
<tr>
<th></th>
<th>OPC (kg)</th>
<th>PFA (kg)</th>
<th>r-FA (kg)</th>
<th>LWA (kg)</th>
<th>Sand (kg)</th>
<th>Water (kg)</th>
<th>w/b</th>
<th>SP (L/m³)</th>
<th>VMA (L/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r-FA-0</td>
<td>400</td>
<td>100</td>
<td>0</td>
<td>615</td>
<td>450</td>
<td>168</td>
<td>0.34</td>
<td>6.0</td>
<td>2.9</td>
</tr>
<tr>
<td>r-FA-150</td>
<td>400</td>
<td>100</td>
<td>150</td>
<td>580</td>
<td>450</td>
<td>168</td>
<td>0.34</td>
<td>6.0</td>
<td>-</td>
</tr>
<tr>
<td>r-FA-180</td>
<td>400</td>
<td>100</td>
<td>180</td>
<td>560</td>
<td>450</td>
<td>168</td>
<td>0.34</td>
<td>6.0</td>
<td>-</td>
</tr>
<tr>
<td>FBA-30</td>
<td>400</td>
<td>100</td>
<td>150</td>
<td>580</td>
<td>300</td>
<td>110</td>
<td>0.34</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>FBA-50</td>
<td>400</td>
<td>100</td>
<td>150</td>
<td>580</td>
<td>215</td>
<td>180</td>
<td>0.34</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>FBA-70</td>
<td>400</td>
<td>100</td>
<td>150</td>
<td>580</td>
<td>108</td>
<td>270</td>
<td>0.34</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>FBA-100</td>
<td>400</td>
<td>100</td>
<td>150</td>
<td>580</td>
<td>-</td>
<td>365</td>
<td>0.34</td>
<td>6.0</td>
<td></td>
</tr>
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</table>
# Fresh Properties

<table>
<thead>
<tr>
<th></th>
<th>L-box ratio (%)</th>
<th>Segregation ratio (%)</th>
<th>Wet density (kg/m³)</th>
<th>Slump flow (After 2 hours) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Series I</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>r-FA-0</td>
<td>90.6</td>
<td>10.3</td>
<td>1740</td>
<td>860</td>
</tr>
<tr>
<td>r-FA-150</td>
<td>90.4</td>
<td>7.1</td>
<td>1860</td>
<td>805</td>
</tr>
<tr>
<td>r-FA-180</td>
<td>86.7</td>
<td>10.2</td>
<td>1880</td>
<td>660</td>
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<tr>
<td><strong>Series II</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FBA-30</td>
<td>83.3</td>
<td>8.5</td>
<td>1810</td>
<td>715</td>
</tr>
<tr>
<td>FBA-50</td>
<td>93.8</td>
<td>8.3</td>
<td>1740</td>
<td>730</td>
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<tr>
<td>FBA-70</td>
<td>87.5</td>
<td>9.2</td>
<td>1730</td>
<td>735</td>
</tr>
<tr>
<td>FBA-100</td>
<td>93.8</td>
<td>11.0</td>
<td>1720</td>
<td>670</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th></th>
<th>Shrinkage (112 days) (x10^{-6})</th>
<th>Chloride permeability (C)</th>
<th>Oven-dry density (kg/m^3)</th>
<th>Saturated density (kg/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Series I</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>r-FA-0</td>
<td>462</td>
<td>1308</td>
<td>1715</td>
<td>1921</td>
</tr>
<tr>
<td>r-FA-150</td>
<td>680</td>
<td>1396</td>
<td>1692</td>
<td>1890</td>
</tr>
<tr>
<td>r-FA-180</td>
<td>409</td>
<td>1439</td>
<td>1865</td>
<td>1937</td>
</tr>
<tr>
<td><strong>Series II</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FBA-30</td>
<td>619</td>
<td>1129</td>
<td>1694</td>
<td>1909</td>
</tr>
<tr>
<td>FBA-50</td>
<td>510</td>
<td>1569</td>
<td>1644</td>
<td>1845</td>
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<tr>
<td>FBA-70</td>
<td>472</td>
<td>1143</td>
<td>1614</td>
<td>1805</td>
</tr>
<tr>
<td>FBA-100</td>
<td>723</td>
<td>1818</td>
<td>1557</td>
<td>1820</td>
</tr>
</tbody>
</table>
Slump flow
Compressive strength

150 and 180 rFA mixes show similar compressive strength but higher than that without rFA

Highest compressive strength→30% FBA replacement
Tensile splitting Strength

![Chart](chart.png)
E-values

![Bar chart showing E-values for different FBA contents: 0% FBA, 30% FBA, 50% FBA, 70% FBA, 100% FBA. The values increase as the FBA content increases.](image)
E-value vs Compressive strength

The diagram shows the relationship between the modulus of elasticity (GPa) and compressive strength (MPa). The data is compared with experimental data and standards such as ACI 363R-92 and BS 8110-2 (1985). The graph illustrates the trend and variability of these properties in various materials.
Compressive Strength

- The use of r-FA increased the compressive strength.
- Low 1-day strength (4.5 MPa) without the use of r-FA.
- The 1-day strengths were 16 and 21 MPa for mixtures with 150 and 180 kg/m$^3$ of r-FA respectively.
Conclusions: I

Normal weight SCC

- r-FA could be used as a replacement of viscosity agent.
- The fresh properties of SCC with r-FA were satisfactory.
- The compressive strength of SCC increased with an increase in r-FA content.
Conclusions: II

- Elastic modulus also increased with an increase in r-FA content.
- Resistance to chloride ion penetration was improved as the r-FA content increased.
- A good correlation between strength and elastic modulus.
Conclusions: III

Lightweight SCC

- R-FA and FBA can be used to produce lightweight SCC
- The fresh properties of lightweight SCC was satisfactory.
- It was found that slump flow reached the maximum 30 minutes after mixing.
- The oven dried density of lightweight SCC was about 1650 kg/m³.
Conclusions: IV

- The addition of r-FA significantly increased the compressive strength of LWSCC.
- The incorporation of r-FA significantly improved the 1-day compressive strength.
- Mix with 30 FBA achieved the highest strength.
Thank you for your attention!