Assessment of Concrete Deformation and Failure Behavior during a Standard Fire Test and a Controlled Heating Rate Test

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ACI Spring Convention
Kansas City, MO
April 12, 2015
Normal and High Strength Concrete Column Behavior

Observations from Column Fire Testing

• The failure of the RC column is governed by the strength of the concrete
  • Concrete carries an increasing portion of the applied column load as the steel temperature increases resulting in yielding and decreasing strength.
  • The concrete strength also decreases with temperature

• The fire resistance decreases with increasing load intensity (loss of strength is higher in HSC than in NSC).
Motivation

• How comparable are concrete behaviors observed from simulated controlled heating rate fire tests to that of concrete behavior in standard fire tests?
<table>
<thead>
<tr>
<th>Concrete Mix</th>
<th>NSC</th>
<th>HSC</th>
<th>VHSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone Coarse Aggregate (kg/m³)</td>
<td>1032</td>
<td>785</td>
<td>787</td>
</tr>
<tr>
<td>Limestone Fine Aggregate (kg/m³)</td>
<td>795</td>
<td>880</td>
<td>859</td>
</tr>
<tr>
<td>Limestone Intermediate Aggregate (kg/m³)</td>
<td>-</td>
<td>349</td>
<td>288</td>
</tr>
<tr>
<td>Type 1 Cement (kg/m³)</td>
<td>203</td>
<td>259</td>
<td>262</td>
</tr>
<tr>
<td>Slag Cement (kg/m³)</td>
<td>110</td>
<td>146</td>
<td>141</td>
</tr>
<tr>
<td>Mid-Range Water Reducer (Super P) (L)</td>
<td>0.95</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Water (kg/m³)</td>
<td>133</td>
<td>114.5</td>
<td>105</td>
</tr>
<tr>
<td>Water/Cementitious Materials Ratio</td>
<td>0.43</td>
<td>0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>Compressive Strength (MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 days</td>
<td>51.5</td>
<td>63.4</td>
<td>90.0</td>
</tr>
<tr>
<td>At Time of Testing</td>
<td>52.5</td>
<td>77.5</td>
<td>107</td>
</tr>
</tbody>
</table>

Specimens around 80-87% internal RH prior to testing

VHSC: conditioning at 45°C

Specimens: 100 mm by 100 mm cross section area (length 450 & 900 mm)
Test Setup

Volume Stable Mullite Tubes

Load Beam

Unloaded beam with embedded Thermocouples

Base

Ram

Roof
Testing Procedure

- Specimen Preparation
  - Loaded Prism
  - Free Expansion Prism
- Specimen Loaded to the Predetermined Load
- Thermal Profile Started
- Sustained Load During the Cooling Phase

Specimen Failure at 740°C
Temperature Development in Standard Fire Test

Temperature Development Over Time for Core, Surface, and Quarter Measurements.
Temperature Development in Controlled Heating Rate Test

![Temperature Development Graph](image-url)
Total Deformation

- Total deformation of concrete is expressed as the sum of four strain components as follows:
  \[ \varepsilon = \varepsilon_{th}(T) + \varepsilon_{t\sigma}(\sigma, T) + \varepsilon_{cr}(\sigma, T, t) + \varepsilon_{tr}(\sigma, T) \]

- Components of Total Strain
  - Thermal Strain (\(\varepsilon_{th}\))
  - Stress Related Strain (\(\varepsilon_{t\sigma}\))
  - Creep Strain (\(\varepsilon_{cr}\))
  - Transient Strain (\(\varepsilon_{tr}\))
Total Strain Curves – Controlled Heating Rate

- Specimen Failure

Temperature (°C)

% Total Strain

α = 0.167 (52.5 MPa)
α = 0.330 (52.5 MPa)
α = 0.500 (52.5 MPa)

α = 0.167 (77.5 MPa)
α = 0.330 (77.5 MPa)
α = 0.500 (77.5 MPa)
Total Strain Comparison
Standard Fire and Controlled Heating

* Specimen Failure
NSF = Non-Standard Fire
During and After Standard Fire Test

- Core temperatures less than 150°C
- Specimen Failure for initial load level $\alpha = 0.33$
- Specimen behavior similar at $\alpha = 0.167$ and $\alpha = 0.25$
- Longitudinal Crack develops during test (450 - 500°C)
- Spalling near 110 °C core temperature
Total Strain Comparison
Standard Fire and Controlled Heating

\[ \alpha \approx 0.33 \]

controlled \( \checkmark \)

\[ 20\% \text{ Spalling} \]

* Specimen Failure
NSF = Non-Standard Fire

- ASTM, \( \alpha = 0.250 \)
- ASTM, \( \alpha = 0.167 \) (1)
- ASTM, \( \alpha = 0.167 \) (2)
- 600°C, \( \alpha = 0.167 \) (NSF)
- 800°C, \( \alpha = 0.167 \) (NSF)
Observations

• The deformation and failure behavior was similar for concrete prisms when load intensity and average core temperature was accounted for.

• Results indicated that deformations exceeding $\approx 1\%$, whether they occur during heating or cooling, are expected to cause an unstable ‘runaway’ failure.
Acknowledgements

• National Science Foundation Award #0747775

• Center for Innovative Materials Research (CIMR) at Lawrence Technological University

• Assistance During Experimental Research From:
  • Brittany Schuel, Mishi Joshi, Daniel Ziemba, Carl Durden
Thank you!