Properties of the High-Volume Fly Ash Concrete, and its Role in Sustainability of Cement and Concrete

V. M. Malhotra
Potential Advantages of using high volumes of fly ash in concrete

- Reduction in global energy demand
- Economical
- Better concrete
- Use of a byproduct otherwise wasted: disposal problems
- Conservation of resources
- Reduction in CO₂ emissions
Introduction

- High-Volume Fly Ash (HVFA) Concrete was developed at CANMET in 1985.
- This type of concrete has all the attributes of high-performance concrete: excellent mechanical properties and superior durability.
Definition

- High Volumes of Fly Ash
- Low water content
- Low portland cement content
- For low W/CM and/or high slumps; the use of superplasticizer is mandatory
High-Volume Fly Ash Concrete

Typical

Water: 120 kg/m³
Cement: 155 kg/m³
Fly Ash: 215 kg/m³
W/(C+FA) = 0.32
Superplasticizer: 4.5 L/m³
Air-Entrained
## Mixture proportions (variations)

<table>
<thead>
<tr>
<th></th>
<th>Low Strength</th>
<th>High Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>115 kg/m³</td>
<td>110 kg/m³</td>
</tr>
<tr>
<td>Cement</td>
<td>125 kg/m³</td>
<td>180 kg/m³</td>
</tr>
<tr>
<td>Fly ash</td>
<td>165 kg/m³</td>
<td>220 kg/m³</td>
</tr>
<tr>
<td>W/CM</td>
<td>0.40</td>
<td>0.28</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>3 L/m³</td>
<td>5.5 L/m³</td>
</tr>
<tr>
<td>Air-Entrained</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
HVFA Concrete without Superplasticizer

- The total amounts of cementing materials and water in the mixture are higher than for the superplasticized HVFA concrete.
- It is produced by taking advantage of the reduction of water demand of the mixture due to the presence of large proportion of fly ash.
- To insure proper performance, especially durability, the W/CM must be kept as low as possible, preferably below 0.40.
## Reduction of Water Demand

<table>
<thead>
<tr>
<th>Fly Ash</th>
<th>W/CM</th>
<th>Water, kg/m³</th>
<th>Cement, kg/m³</th>
<th>Fly Ash, kg/m³</th>
<th>Slump, mm</th>
<th>Water Reduction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref.</td>
<td>0.43</td>
<td>170</td>
<td>396</td>
<td>0</td>
<td>55</td>
<td>-</td>
</tr>
<tr>
<td>F1</td>
<td>0.38</td>
<td>151</td>
<td>181</td>
<td>221</td>
<td>55</td>
<td>11.2</td>
</tr>
<tr>
<td>F2</td>
<td>0.39</td>
<td>155</td>
<td>180</td>
<td>220</td>
<td>55</td>
<td>8.8</td>
</tr>
<tr>
<td>F3</td>
<td>0.37</td>
<td>146</td>
<td>180</td>
<td>220</td>
<td>65</td>
<td>14.1</td>
</tr>
<tr>
<td>F4</td>
<td>0.35</td>
<td>140</td>
<td>182</td>
<td>222</td>
<td>55</td>
<td>17.6</td>
</tr>
<tr>
<td>F5</td>
<td>0.34</td>
<td>138</td>
<td>182</td>
<td>222</td>
<td>55</td>
<td>18.8</td>
</tr>
<tr>
<td>F6</td>
<td>0.38</td>
<td>154</td>
<td>181</td>
<td>222</td>
<td>70</td>
<td>9.4</td>
</tr>
<tr>
<td>F7</td>
<td>0.38</td>
<td>152</td>
<td>179</td>
<td>219</td>
<td>55</td>
<td>10.6</td>
</tr>
<tr>
<td>F8</td>
<td>0.34</td>
<td>137</td>
<td>182</td>
<td>222</td>
<td>65</td>
<td>19.4</td>
</tr>
</tbody>
</table>
Properties of the Fresh Concrete
Workability

- In general, the HVFA concrete possesses excellent cohesiveness and workability (if properly designed). This type of concrete will therefore exhibit good pumpability, compactability and finishability characteristics.
Autogenous Temperature Rise

- In mass concrete and rather massive structural elements, it is important that the temperature rise be kept as low as possible to avoid thermal cracking.
- Temperature Rise of the HVFA concrete is rather low.
- 3.05x3.05x3.05-meters blocks
  - HVFA Concrete: rise = 35°C
  - Portland cement concrete: rise = 65°C
Bleeding

• The bleeding of the HVFA Concrete ranges from very low to negligible because of its low water content.

• Proper care should be taken to prevent plastic shrinkage
Setting Time

- Somewhat longer than that of conventional concrete: about 3 hours, in general.
  - Retardation will be enhanced by cold weather
  - Can be beneficial in hot weather
- In general, the HVFA concrete does not show unacceptable retardation in setting time.
Curing

• As for any type of concrete, the need for adequate curing cannot be over-emphasized for high-volume fly ash concrete.

• To ensure satisfactory early- and later-age strength development, low permeability, and long-term resistance to aggressive media, it is most essential that HVFAC be protected from premature drying by curing for an adequate length of time.

• The duration of curing will depend on the nature of exposure conditions.
Mechanical Properties of the High-Volume Fly Ash Concrete
Compressive Strength of HVFAC

- Compressive strengths in the range of 8 MPa (12 MPa) at one day, 35 MPa (45 MPa) at 28 days, 43 MPa (55 MPa) at 91 days, and 55 (70 MPa) MPa at one year were obtained with HVFA concrete made with normal Type I (Type 10) cement.
Compressive Strength Development of HVFA Concrete (Typical)

- HVFA CSA Type 10
- HVFA CSA Type 30
- Conventional Concrete

Graph: Compressive Strength vs. Age, Days
- Y-axis: Compressive Strength, MPa
- X-axis: Age, Days

Legend:
- Blue line: HVFA CSA Type 10
- Gray line: HVFA CSA Type 30
- Red line: Conventional Concrete

Data for typical compressive strength development of HVFA concrete over time.
Flexural and Splitting-Tensile Strengths

- Flexural strengths of the order of 4.5 and 6.0 MPa can be obtained at 14 and 91 days, respectively.
- Splitting-Tensile strength is of the order of 3.5 MPa.
Young’s Modulus of Elasticity

- Of the order of 35 and 38 GPa at 28 and 91 days, respectively
- High modulus due to unreacted fly ash acting as fine aggregate
Drying Shrinkage

- Comparable to, or lower than that of conventional portland cement concrete, with values of the order of $500 \times 10^{-6}$ after 64 weeks of air drying
Creep

• Can be considered low with specific creep values ranging from 24 to 32x10^{-6} per MPa of stress

• Low creep due to unreacted fly ash particles acting as fine aggregate
Durability of High-Volume Fly Ash Concrete
Water Permeability

• Less than or equal to $10^{-13}$ m/s
• Less than half the value of a conventional concrete with comparable strength
Freezing and Thawing Cycling

- Excellent resistance to freezing and thawing cycling
  - Durability factors in excess of 90 after being subjected to 1000 cycles in ASTM C 666 Procedure A
Resistance to Chloride Ion Penetration (ASTM C 1202)

- It consists of monitoring the amount of electrical current passed through 51-mm thick slices of 102-mm nominal diameter cores or cylinders during a 6-hour period.
## Resistance to Chloride Ion Penetration (ASTM C 1202)

<table>
<thead>
<tr>
<th>Charge Passed (coulombs)</th>
<th>Chloride Ion Penetrability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 4,000</td>
<td>High</td>
</tr>
<tr>
<td>2,000 – 4,000</td>
<td>Moderate</td>
</tr>
<tr>
<td>1,000 – 2,000</td>
<td>Low</td>
</tr>
<tr>
<td>100 – 1,000</td>
<td>Very Low</td>
</tr>
<tr>
<td>&lt; 100</td>
<td>Negligible</td>
</tr>
</tbody>
</table>
Penetration of Chloride Ions HVFAC

Typical Results

- Very high resistance to penetration of chloride ions in tests performed according to ASTM C 1202
  - 28 days: 500 to 2000 coulombs
  - 91 days: 200 to 700 coulombs
  - 1 year: about 150 coulombs
### Penetration of Chloride Ions HVFAC

**Rapid Chloride Permeability Test ASTM C 1202**

<table>
<thead>
<tr>
<th>W/CM</th>
<th>Cement Type</th>
<th>28 day</th>
<th>91 day</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33</td>
<td>45% FA</td>
<td>1440</td>
<td>480</td>
</tr>
<tr>
<td>0.33</td>
<td>55% FA</td>
<td>1790</td>
<td>620</td>
</tr>
<tr>
<td>0.45</td>
<td>Normal</td>
<td>-</td>
<td>3940</td>
</tr>
</tbody>
</table>
Resistance to Chloride Ion Penetration (AASHTO T 259)

- Slabs are subjected to continuous ponding with 3-percent sodium chloride solution for 90 days.
- Samples for chloride ion analysis are then taken from the slabs at different depths.
- The chloride content of each sample is then determined.
### Penetration of Chloride Ions HVFAC

**Ponding Test**

<table>
<thead>
<tr>
<th>W/CM</th>
<th>Cement Type</th>
<th>Chloride Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.6–7 mm</td>
</tr>
<tr>
<td>0.33</td>
<td>45% FA</td>
<td>0.23</td>
</tr>
<tr>
<td>0.33</td>
<td>55% FA</td>
<td>0.23</td>
</tr>
<tr>
<td>0.45</td>
<td>Normal</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Sulphate Attack HVFAC

- Excellent resistance to sulphate attack
  - Low permeability
  - Reduction in C\textsubscript{3}A and Ca(OH)\textsubscript{2} contents
  - Consumption of Ca(OH)\textsubscript{2} in pozzolanic reaction
Durability in Marine Environment

- 305x305x915-mm prisms exposed to marine environment at Treat Island, Maine for the last 10 years
  - sea water, wetting and drying cycles, freezing and thawing cycles
- No significant deterioration
Durability in Marine Environment

The Treat Island Marine Exposure Site
## Corrosion of Steel Reinforcement

### Probability of corrosion after six months
(half-cell potential method)

<table>
<thead>
<tr>
<th>Material/Control</th>
<th>13 mm</th>
<th>25 mm</th>
<th>51 mm</th>
<th>76 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVFA Class F ash</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>HVFA Class C ash</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Control w/c = 0.32</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Control w/c = 0.43</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Control w/c = 0.55</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Control w/c = 0.76</td>
<td>High</td>
<td>High</td>
<td>Middle</td>
<td>Low</td>
</tr>
</tbody>
</table>
Carbonation

• The use of fly ash in concrete reduces the CH content and the permeability of concrete. Therefore, fly ash concrete should normally be more resistant to carbonation (provided the fly ash concrete is adequately cured).

• The average carbonation depth of Blocks made with HVFAC was of the order of 12 mm after 15 years.
Environment Concerns

• The radioactivity of a substance can be described in terms of the amount of radioactivity it emits (curie), picocurie (pCi, $1 \times 10^{-12}$ curie) is used;

• Measured emission rates from blocks made from fly ash have resulted in a radon equilibrium concentration in the range of 0.1 to 0.9 pCi/L.
Environment Concerns

- For comparison, the Environment Protection Agency (EPA) “Action level” for radon in indoor air spaces is 4 pCi/L;
- CANMET study have shown that regardless of the type of the fly ash used, percentage of the fly ash, and w/cm of the concrete, none of the trace metals in the leachates from the fly ash concrete exceeded the regulated concentration levels in the TCLP regulatory test. The concrete incorporating the fly ashes is, therefore, considered stable.
Conclusion

- The High-Volume Fly Ash Concrete provides an excellent alternative to conventional concrete; it is environmentally friendly and demonstrates the attributes of high-performance concrete.
Conclusion

- The high-performance, high-volume fly ash concrete can be produced with cements and fly ashes having a wide range of chemical compositions and physical properties.
Conclusion

- This concrete has adequate early-age and excellent later-age mechanical properties and demonstrates remarkable performance in most durability aspects.