Metakaolin Used in Fibre Reinforced Centrifugal Placed Concrete in Mine in Western Canada

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Content

- Part One: Metakaolin (MK) introduction
- Part Two: MK fiber reinforced concrete trial mix
- Part Three: Centrifugal Placed Concrete (CPC) mock-up: Mix A, Mix B
- Part Four: CPC field application, Mix C, Mix D
- Part Five: Compressive strength, boiled absorption and volume of permeable voids, flexural toughness
- Part Six: Sustainability
Introduction to Metakaolin (MK)

- Mined from natural Kaolin (aluminum silicate), calcinated at high temperature (800°C) through a dry process.
- Type N Supplementary Cementing Material (SCM) in ASTM C618 and CSA A3001-03
- Product research was conducted by AMEC including trial mix, compressive strength testing, shrinkage testing, rapid chloride penetration testing, freeze-thaw testing, and AAR testing.
# Introduction to MK – Chemical properties

## Chemical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>CSA</th>
<th>ASTM/AASHTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₃</td>
<td>0.06 %</td>
<td>3% Max</td>
<td>4% Max</td>
</tr>
<tr>
<td>Sum (SiO₂, Al₂O₃, Fe₃O₃)</td>
<td>93.6 %</td>
<td></td>
<td>70% Min</td>
</tr>
<tr>
<td>Total Alkalis as Na₂O</td>
<td>1.4 %</td>
<td></td>
<td>3% Max</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>0.2 %</td>
<td>10% Max</td>
<td>10% / 5% Max</td>
</tr>
<tr>
<td>Loss On Ignition - 800°C</td>
<td>1 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Available Alkalis as Na₂O</td>
<td>0.22 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Physical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>CSA</th>
<th>ASTM/AASHTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness (45 um % retained)</td>
<td>3 %</td>
<td>34% Max</td>
<td>34% Max</td>
</tr>
<tr>
<td>Density</td>
<td>2.56 g/cc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autoclave expansion</td>
<td>0.02 %</td>
<td>0.8% Max</td>
<td>0.8% Max</td>
</tr>
<tr>
<td>Water Requirement</td>
<td>105 % of Control</td>
<td></td>
<td>115% Max</td>
</tr>
<tr>
<td>Strength Activity Index 7 day</td>
<td>121 % of Control</td>
<td></td>
<td>75% Min</td>
</tr>
<tr>
<td>Strength Activity Index 28 day</td>
<td>116 % of Control</td>
<td></td>
<td>75% Min</td>
</tr>
</tbody>
</table>

## Uniformity Requirements

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Variation from Ave.</th>
<th>CSA</th>
<th>ASTM/AASHTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1 %</td>
<td></td>
<td>5% Max</td>
<td></td>
</tr>
<tr>
<td>Fineness (45 um % retained)</td>
<td>0.4 %</td>
<td></td>
<td>5% Max</td>
<td></td>
</tr>
</tbody>
</table>
## Fibre Reinforced CPC Mix Designs

<table>
<thead>
<tr>
<th>Material [kg/m³]</th>
<th>Mix A: Natural Pozzolan (30%)</th>
<th>Mix B: Silica Fume (10%)</th>
<th>Mix C: Metakaolin (20%)</th>
<th>Mix D: Metakaolin/Silica Fume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement Type GU</td>
<td>386</td>
<td>430</td>
<td>418</td>
<td>420</td>
</tr>
<tr>
<td>Natural Pozzolan</td>
<td>119</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silica Fume</td>
<td></td>
<td>44</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>Metakaolin</td>
<td></td>
<td></td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Fine Aggregate (SSD)</td>
<td>1516</td>
<td>1655</td>
<td>1630</td>
<td>1630</td>
</tr>
<tr>
<td>Water</td>
<td>227</td>
<td>200</td>
<td>193</td>
<td>210</td>
</tr>
<tr>
<td>Macro-Synthetic Fibre</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
Metakaolin Mix – Laboratory Hand Cast Trial
Metakaolin Mix
Laboratory Hand Cast Trial Results: Compressive Strength

MK Mix Compressive Strength

Age (days)

Compressive Strength (MPa)

Graph showing the compressive strength of MK mix over time.
Metakaolin FRS
Laboratory Hand Cast Trial Results: Flexural Toughness

ASTM C1550 Round Panel Test
Cast Concrete Panel at 7 days

<table>
<thead>
<tr>
<th>Property</th>
<th>At centre point deflection of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 mm</td>
</tr>
<tr>
<td>Corrected Load [kN]</td>
<td>13.7</td>
</tr>
<tr>
<td>Load vs. First Peak Load</td>
<td>73%</td>
</tr>
<tr>
<td>Corrected Energy [J]</td>
<td>85</td>
</tr>
</tbody>
</table>

Peak Load = 18.7 kN
Panel broken into three pieces with typical Y yield line failure pattern
Metakaolin Mix
Centrifugal Placed Concrete (CPC) Mock-up

- Centrifugal placement
- Compressed air used to rotate spinner head at 4000-5000 rpm
- No accelerator added
- Slump: 150 mm at the end of hose at spinner head
Metakaolin CPC Field Application

- Underground Mine Raise Bore Shaft in British Columbia, Canada
- 11.5 ft (3.5m) in diameter, 951 ft (290 m) deep
- CPC applied 2 in (50 mm) thick
- Mine set up a batch plant for batching CPC
- Time of placement : June, 2009
CPC Field Application

- Plastic concrete: 150 mm slump at the end of hose, air content 2% as shot
- Low rebound
- Two test panels (800 mm diameter, 75 mm thick) were produced every day and tested at 3 and 7 days.
- Fiber dosage 5 kg/m³
CPC Performance – Compressive Strength

Centrifugal Placed Fiber Reinforced Concrete

Performance Requirement:
Compressive strength minimum 30 MPa at 7 days, 40 MPa at 28 days

Mix A: Natural Pozzolan  Mix B: Silica Fume  Mix C: Metakaolin  Mix D: Metakaolin + Silica Fume
CPC Performance
- Volume of Permeable Voids & Boiled Absorption (ASTM C642)

Performance Requirement:
Maximum Value of Boiled Absorption 8%; Maximum Value of Permeable Voids 17%
CPC Performance – Energy (ASTM C1550)

Centrifugal Placed Fiber Reinforced Concrete

- Mix A: Natural Pozzolan
- Mix B: Silica Fume
- Mix C: Metakaolin
- Mix D: Metakaolin + Silica Fume

Performance requirement:
Flexural toughness 320 J at 28 days
### Metakaolin CPC Performance
#### Flexural Toughness vs. Number of Fibers

<table>
<thead>
<tr>
<th>Date Cast/Shot</th>
<th>Panel #</th>
<th>Mix Designation</th>
<th>Test Age (days)</th>
<th>Compressive Strength (MPa)</th>
<th>RDP Corrected First Crack Load (kN)</th>
<th>RDP Corrected Energy (J)</th>
<th>No. of Fibers in Fracture Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-Jun-09</td>
<td>1</td>
<td>Mix C</td>
<td>37</td>
<td>62.9</td>
<td>27.1</td>
<td>313</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>37</td>
<td>70.2</td>
<td>26.0</td>
<td>157</td>
<td>228</td>
</tr>
<tr>
<td>13-Jun-09</td>
<td>1</td>
<td>Mix C</td>
<td>35</td>
<td>71.9</td>
<td>24.4</td>
<td>144</td>
<td>236</td>
</tr>
<tr>
<td></td>
<td>2(1)</td>
<td></td>
<td>35</td>
<td>74.1</td>
<td>26.1</td>
<td>167</td>
<td>172</td>
</tr>
<tr>
<td>14-Jun-09</td>
<td>2(2)</td>
<td>Mix C</td>
<td>34</td>
<td>71.2</td>
<td>19.5</td>
<td>178</td>
<td>248</td>
</tr>
</tbody>
</table>

(1) Broken into two pieces  
(2) Not a Y type failure

![Graph showing the relationship between toughness and number of fibers in the fracture surface.](image)
Metakaolin CPC Performance

MK CPC
- 20% replacement of cement used in both trial mixes and large mine project
- Higher compressive strength than natural pozzolan concrete
- Good workability, good compaction with low values of boiled absorption & volume of permeable voids
- Performed well with macro synthetic fiber reinforcement

Centrifugal Placed Concrete (CPC) Method
- Cost effective: completed in 10 days (much shorter than previously used: conventional robotically placed dry-mix steel fiber reinforced shotcrete lining completed in 6 weeks)
- First time used in North America (D.R. Morgan., Centrifugal Placed Concrete for Lining Horizontal Pipes, Culverts, and Vertical shafts, 3rd International Conference/Engineering Developments in Shotcrete. Queenstown, New Zealand 2010 March)
- Now to be used for lining several more raise bore shafts in mines in North America
Metakaolin in Concrete – Sustainability

- MK is a SCM
- MK concrete has high compressive strength, and good durability
- LEED New Construction MR 4.1 & 4.2:
  - Cement Reduction (%) = \(2 \times \frac{\text{cement in base mix} - \text{cement in SCM mix}}{\text{cement in base mix}}\)
  - MK replaces 20% cement by mass; LEED equates this to a 40% cement reduction
Metakaolin in Concrete – LEED Compliance

- LEED New Construction, MR 4.1 & 4.2:
  - 1 point for 7.5% (post-consumer + ½ post-industrial)
  - 2 points for 15% (post-consumer + ½ post-industrial)
- LEED specifies post-consumer recycled content and post-industrial content, such as fly ash, slag, silica fume, incinerator ashes, GS-CEM.
- Calcining kaolin at 800°C generates 55% less GHG vs. cement production.
- Calculation of CO$_2$ emitted for 1 ton cement production (1 ton) vs. 1 ton metakaolin production (to be determined)
Metakaolin in Concrete – LEED Compliance

- MRc5 Regional Materials
- MRc8 Durable Building (LEED Canada NC 1.0)
- MRc2 Environmentally Preferable Products (LEED Canada for Homes 2009)
AMEC’s Leading Role in Industry

- 1976 Converted ready mix concrete producers in Western Canada into routine use of fly ash in everyday concretes
- 1983 first time use of silica fume in shotcrete in North America
- 1998 founding member of America Shotcrete Association
- 2000 Full characterization Teck Commico ground metallurgical slag cementing material, later become integral hardener with brand name of “Hard Cem”
- 2002-2008 use of high volume fly ash (up to 48%) in Little Mountain Reservoir and Seymour Capilano Filtration Plan projects in Vancouver
- 2005 Full characterization of use of calcined metakaolin in concrete
- 2008/9 Dow Jones Sustainability Index